CLIMATE AND ENERGY IMPLICATIONS OF CRYPTO-ASSETS IN THE UNITED STATES

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Statement of Purpose

On March 9, 2022, President Biden signed Executive Order 14067: “Ensuring Responsible Development of Digital Assets,”[1] to support responsible digital asset development, in line with our climate change objectives, and for the benefit of everyone in America. The President directed the White House Office of Science and Technology Policy (OSTP), and its partners from the Executive Office of the President and across federal agencies, to examine: the connections between distributed ledger technologies (DLT) and energy transitions, the potential for these technologies to impede or advance efforts to tackle climate change at home and abroad, and the impacts these technologies have on the environment. This report provides the assessment directed by Executive Order 14067.

About the Interagency Process

The creation of this report was coordinated through an interagency process led by Assistant to the President for National Security Affairs and the Assistant to the President for Economic Policy, as described in Section 3 of Executive Order 14067. A list of departments and agencies involved in this interagency process can be found in the Interagency Policy Committee section of the Appendices.

Suggested Citation

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About the Office of Science and Technology Policy

The Office of Science and Technology Policy (OSTP) was established by the National Science and Technology Policy, Organization, and Priorities Act of 1976 to provide the President and others within the Executive Office of the President with advice on the scientific, engineering, and technological aspects of the economy, national security, homeland security, health, foreign relations, the environment, and the technological recovery and use of resources, among other topics. OSTP leads interagency science and technology policy coordination efforts, assists the Office of Management and Budget with an annual review and analysis of federal research and development in budgets, and serves as a source of scientific and technological analysis and judgment for the President with respect to major policies, plans, and programs of the federal government. More information is available at http://www.whitehouse.gov/ostp.

Summary and Recommendations

The U.S. National Climate Assessment and the Intergovernmental Panel on Climate Change (IPCC) show that reducing global anthropogenic greenhouse gas (GHG) emissions to net-zero by mid-century will prevent the most severe damages to human health, ecosystems, and infrastructure. These climate-driven damages include deaths caused by: heat waves; loss of forests, homes, and infrastructure from increasing wildfires; flooding and extreme weather events; property loss; damage to roads, bridges, public transit systems and the energy system; inundation of coastal areas by sea level rise and storm surges; droughts; damage to crops; and other harms to the ecosystems that sustain people.[2,3] The damages intensified by climate change are not borne equally; underserved communities are often disproportionally burdened with the most severe impacts from climate change.[4] Climate change is expensive: in 2021, climate disasters cost the United States $145 billion.[5] Climate change also poses risks to taxpayers, the federal budget, and federal facilities; without increased action, climate change could reduce U.S. gross domestic product by 3% to 10%, and U.S. federal revenue by 7% annually by the end of the century.[6] The United States is committed to combatting the climate crisis and reducing GHG emissions by 50% to 52% below 2005 levels by 2030, achieving a carbon pollution-free electricity grid by 2035, and reaching net-zero emissions no later than 2050, all while prioritizing environmental justice.

At the same, the use of digital assets based on distributed ledger technology is expanding. Digital assets are a form of value, represented digitally. As an emerging technological innovation, digital assets have provided some benefits and value for some U.S. residents and businesses, and have the potential for future benefits with emerging uses. Crypto-assets are digital assets that are implemented using cryptographic techniques, and have a total current global market capitalization of nearly $1 trillion. However, some crypto-asset technologies currently require a considerable amount of electricity for asset generation, ownership, and exchange. Electricity usage from digital assets is contributing to GHG emissions, additional pollution, noise, and other local impacts, depending on markets, policies, and local electricity sources. Depending on the energy intensity of the technology used, crypto-assets could hinder broader efforts to achieve net-zero carbon pollution consistent with U.S. climate commitments and goals.

The U.S. government has a responsibility to ensure electric grid stability, enable a clean energy future, and protect communities from pollution and climate change impacts. This report explores the challenges and opportunities of crypto-assets for energy and climate change issues in the United States, and answers four main questions asked in Executive Order 14067:

1. How do digital assets affect energy usage, including grid management and reliability, energy efficiency incentives and standards, and sources of energy supply?
2. What is the scale of climate, energy, and environmental impacts of digital assets relative to other energy uses, and what innovations and policies are needed in the underlying data to enable robust comparisons?
3. What are the potential uses of blockchain technology that could support climate monitoring or mitigating technologies?

4. What key policy decisions, critical innovations, research and development, and assessment tools are needed to minimize or mitigate the climate, energy, and environmental implications of digital assets?

How do digital assets affect energy usage, including grid management and reliability, energy efficiency incentives and standards, and sources of energy supply?

Crypto-assets use a significant amount of electricity.

From 2018 to 2022, annualized electricity from global crypto-assets grew rapidly, with estimates of electricity usage doubling to quadrupling.[7,8,9] As of August 2022, published estimates of the total global electricity usage for crypto-assets are between 120 and 240 billion kilowatt-hours per year, a range that exceeds the total annual electricity usage of many individual countries, such as Argentina or Australia. This is equivalent to 0.4% to 0.9% of annual global electricity usage,[10,11] and is comparable to the annual electricity usage of all conventional (i.e., non-crypto-asset) data centers in the world.[12] The United States is estimated to host about a third of global crypto-asset operations, which currently consume about 0.9% to 1.7% of total U.S. electricity usage. This range of electricity usage is similar to all home computers or all residential lighting in the United States.[13] Crypto-asset mining is also highly mobile. The U.S. share of global mining from Bitcoin, the largest crypto-asset, rose from 3.5% in 2020 to 38% today, with U.S. electricity usage for crypto-asset mining, while still relatively small, tripling since January 2021.

Despite the potential for rapid growth, future electricity demand from crypto-asset operations is uncertain. Electricity usage can change as crypto-asset miners ramp their activities up or down in response to market value fluctuations, and as they adopt new equipment and technologies. Annualized global crypto-asset electricity usage grew by more than 67% from July 2021 to January 2022, and then fell by 17% by August 2022. The ability for rapid growth in crypto-asset electricity usage raises concerns about fast increases in electricity usage, and subsequent impacts on consumers and the grid. For example, Texas has emerged as an increasingly attractive location for crypto-asset mining, which uses about 3% of local peak electricity demand. Over the next decade, Texas may see an additional 25 GW of new electricity demand from crypto-asset mining — equivalent to a third of existing peak electricity demand in Texas.[14] This increase raises potential challenges for maintaining electricity reliability.

With the recent enactment of the Inflation Reduction Act, federal tax credits and other incentives will spur large-scale development of clean energy to enable the United States to electrify large portions of the transportation, buildings, and industrial sectors.[15] It is critically important that clean energy powers this demand from new electrification. Additionally, rapidly growing new power demand must avoid unmanageable impacts to the grid and use the most efficient technology available. It is also crucial that electricity remains affordable for homes and businesses. This is especially critical in this moment, when the Bipartisan Infrastructure Law is enabling investments in grid modernization and expansion, to ensure resilience in the face of climate-driven weather extremes and fires.[16]

Electricity usage varies substantially with different crypto-asset technologies.

Nearly all crypto-asset electricity usage is driven by consensus mechanisms: the distributed ledger technologies used to mine and verify crypto-assets. The dominant consensus mechanism is called Proof of Work (PoW), which is used by the Bitcoin and Ethereum blockchains. Bitcoin and Ether, their respective crypto-assets, combined, represent more than 60% of total crypto-asset market capitalization. The PoW mechanism is designed to require more computing power as more entities attempt to validate transactions for coin rewards, and this feature helps disincentivize malicious actors from attacking the network. As of August 2022, Bitcoin is estimated to account for 60% to 77% of total global crypto-asset electricity usage, and Ethereum is estimated to account for 20% to 39%.

An alternative, less energy-intensive consensus mechanism, called Proof of Stake (PoS), was estimated to consume up to 0.28 billion kilowatt-hours per year in 2021, less than 0.001% of global electricity usage. Current discussions about reducing crypto-asset electricity usage primarily focus on PoW blockchains, particularly Bitcoin.[17,18] There have been growing calls for PoW blockchains to adopt less energy-intensive consensus mechanisms. The most prominent reaction has been Ethereum's promised launch of "Ethereum 2.0," which uses a PoS consensus mechanism.

What is the scale of climate, energy, and environmental impacts of digital assets relative to other energy uses, and what innovations and policies are needed in the underlying data to enable robust comparisons?

Global electricity generation for the crypto-assets with the largest market capitalizations resulted in a combined 140 ± 30 million metric tons of carbon dioxide per year (Mt CO_2/y), or about 0.3% of global annual GHG emissions.

Crypto-asset activity in the United States is estimated to result in approximately 25 to 50 Mt CO_2/y, which is 0.4% to 0.8% of total U.S. GHG emissions, similar to emissions from diesel fuel used in railroads in the United States. GHG emissions from electricity usage vary by region in the United States; some regions rely more on carbon-intensive fossil fuels, while others use more nuclear and renewable energy sources. Besides purchased grid electricity, crypto-asset mining operations also cause local noise and water impacts from operations, electronic waste, air and other pollution from any direct usage of fossil-fired electricity, and additional air, water, and waste impacts associated with all grid electricity usage. These local impacts can exacerbate environmental justice issues for underserved communities. Broader adoption of crypto-assets, and the potential introduction of new types of digital assets require action by the federal government to encourage and ensure responsible development. This includes minimizing impacts on local communities, dramatically reducing energy intensity, and powering with clean electricity. Digital asset research that emphasizes innovations in next-generation technologies can advance U.S. goals in security, privacy, equity, resilience, and climate objectives.

What are the potential uses of blockchain technology that could support climate monitoring or mitigating technologies?

There is potential for blockchain technologies to play a role in environmental markets, and DLT could potentially enable distributed energy resource coordination, as well as broader supply chain management.[19,20]

DLT is enabling technologies that are being explored in various markets. Still, other solutions might work as well or better. To help the United States meet its climate change commitments, DLT must be deployed in a manner that enables reductions in GHG emissions. The potential benefits of DLT would need to outweigh the additional emissions and other environmental externalities that result from operations to merit its broader use in the carbon credit market ecosystem, relative to the markets or mechanisms that they are displacing. Use cases are still emerging, and like all emerging technologies, there are potential positive and negative use cases yet to be imagined. The U.S. government should facilitate innovation that addresses market challenges, aligns with environmental and equity objectives, and appropriately ensures customer and investor protection and market integrity.

What key policy decisions, critical innovations, research and development, and assessment tools are needed to minimize or mitigate the climate, energy, and environmental implications of digital assets?

To help the United States meet its climate objectives of a 50% to 52% reduction in GHG emissions by 2030, a carbon pollution-free electricity system by 2035, and a net-zero emissions economy no later than 2050, crypto-asset policy during the transition to clean energy should be focused on several objectives: reduce GHG emissions, avoid operations that will increase the cost of electricity to consumers, avoid operations that reduce the reliability of electric grids, and avoid negative impacts to equity, communities, and the local environment.

The following recommendations aim to: resolve data gaps, manage electricity demand, reduce GHG emissions, reduce electronic waste and pollution, support a clean energy transition that equitably benefits communities across the country, and address longstanding concerns of overburdened and underserved communities.

To ensure the responsible development of digital assets, recommendations include the following actions for consideration:

- **Minimize GHG emissions, environmental justice impacts, and other local impacts from crypto-assets:** The Environmental Protection Agency (EPA), the Department of Energy (DOE), and other federal agencies should provide technical assistance and initiate a collaborative process with states, communities, the crypto-asset industry, and others to develop effective, evidence-based environmental performance standards for the responsible design, development, and use of environmentally responsible crypto-asset technologies. These should include standards for very low energy intensities, low water usage, low noise generation, clean energy usage by operators, and standards that strengthen over time for additional carbon-free generation to match or exceed the additional electricity load of these facilities. Should these measures prove ineffective at reducing impacts, the Administration should explore executive actions, and Congress might consider legislation, to limit or eliminate the use of high energy intensity consensus mechanisms for crypto-asset mining. DOE and EPA should provide technical assistance to state public utility commissions, environmental protection agencies, and the crypto-asset industry to build capacity to minimize emissions, noise, water impacts, and negative economic impacts of crypto-asset mining; and to mitigate environmental injustices to overburdened communities.
- **Ensure energy reliability:** DOE, in coordination with the Federal Energy Regulatory Commission, the North American Electric Reliability Corporation and its regional entities, should conduct reliability assessments of current and projected crypto-asset

mining operations on electricity system reliability and adequacy. If these reliability assessments find current or anticipated risks to the power system as a result crypto-asset mining, these entities should consider developing, updating, and enforcing reliability standards and emergency operations procedures to ensure system reliability and adequacy under the growth of crypto-asset mining.

- **Obtain data to understand, monitor, and mitigate impacts:** The Energy Information Administration and other federal agencies should consider collecting and analyzing information from crypto-asset miners and electric utilities in a privacy-preserving manner to enable evidence-based decisions on the energy and climate implications of crypto-assets. Data should include mining energy usage and fuel mix, power purchase agreements, environmental justice implications, and demand response participation. OSTP could establish a National Science and Technology Council subcommittee to coordinate with other relevant agencies to assess the energy use of major crypto-assets.
- **Advance energy efficiency standards:** The Administration should consider working with Congress to enable DOE and encourage other federal regulators to promulgate and regularly update energy conservation standards for crypto-asset mining equipment, blockchains, and other operations.
- **Encourage transparency and improvements in environmental performance:** Crypto-asset industry associations, including mining firms and equipment manufacturers, should be encouraged to publicly report crypto-asset mining locations, annual electricity usage, GHG emissions using existing protocols, and electronic waste recycling performance.
- **Further research to improve understanding and innovation:** For improved analytical capabilities that can enhance the accuracy of electricity usage estimates and sustainability, the National Science Foundation, DOE, EPA and other relevant agencies could promote and support research and development priorities that improve the environmental sustainability of digital assets, including crypto-asset impact modeling, assessment of environmental justice impacts, and understanding beneficial uses for grid management and environmental mitigation. Research and development priorities should emphasize innovations in next-generation digital asset technologies that advance U.S. goals in security, privacy, equity, and resilience, as well as U.S. climate goals.

1. Motivation and Introduction

Solving the Climate Crisis Is a Key Biden-Harris Administration Priority

Under Executive Order 14008, "Tackling the Climate Crisis at Home and Abroad," the President set a national goal of reducing GHG emissions to net-zero by 2050.[21] Under the Paris Agreement, the United States set a Nationally Determined Contribution of reducing GHGs by 50% to 52% below 2005 levels by 2030, and confirmed the goal to reach net-zero GHG emissions by 2050.[22] Executive Order 14008 recognizes that the nation faces "a climate crisis that threatens our people and communities, public health and economy, and, starkly, our ability to live on planet Earth." This Executive Order addresses this crisis, including through "a government-wide approach that reduces climate pollution in every sector of the economy… [and] protects public health," and directs EPA, OSTP, the Department of the Treasury, and other federal agencies to "prioritize action on climate change" in policy-making processes, among other actions. Executive Order 13990: "Protecting Public Health and the Environment and Restoring Science To Tackle the Climate Crisis" declared that the federal government must be guided by the best science to improve public health, protect our environment, reduce GHG emissions, ensure access to clean air and water, prioritize environmental justice, and create well-paying union jobs.[23]

On August 16, 2022, the President signed into law the Inflation Reduction Act (IRA),[24] which represents the single largest investment in clean energy, GHG emissions reduction, and climate resilience in U.S. history. This law provides $369 billion to fight climate change and enhance U.S. energy security. The IRA is projected to contribute to reducing carbon emissions by 40% from 2005 levels by 2030.[25] Together, the U.S. climate objectives, executive orders, Bipartisan Infrastructure Law,[26] CHIPS and Science Act,[27] and the IRA set the federal government's baseline for action to address the climate crisis.

At the same time, digital asset electricity usage has grown rapidly in the United States. For example, between January 2020 and January 2022, the United States' share of global Bitcoin mining rose from 4.5% to 37.8%.[28] Given the United States' commitment to reduce emissions, the federal government must ensure that use of digital assets in the United States does not impede our ability to meet our climate objectives. This report's assessment and recommendations for the climate and energy implications of digital assets align with federal actions that reduce GHG emissions to protect public health and welfare, and to improve environmental justice.

The United States Must Promote Responsible Development of Digital Assets

President Biden's Executive Order on Ensuring Responsible Development of Digital Assets states, "the United States has an interest in responsible financial innovation," wherein the federal government “must take strong steps to reduce the risks that digital assets could pose to consumers, investors, and business protections…financial inclusion and equity; and climate change and pollution.” To this end, the Executive Order’s principal policy objectives recognize that the federal government “must protect consumers, investors and businesses,” and that the “United States has an interest in ensuring that digital asset technologies and digital payment ecosystems are developed, designed, and implemented in a responsible manner that…reduces negative climate impacts and environmental pollution, as may result from some cryptocurrency mining.”

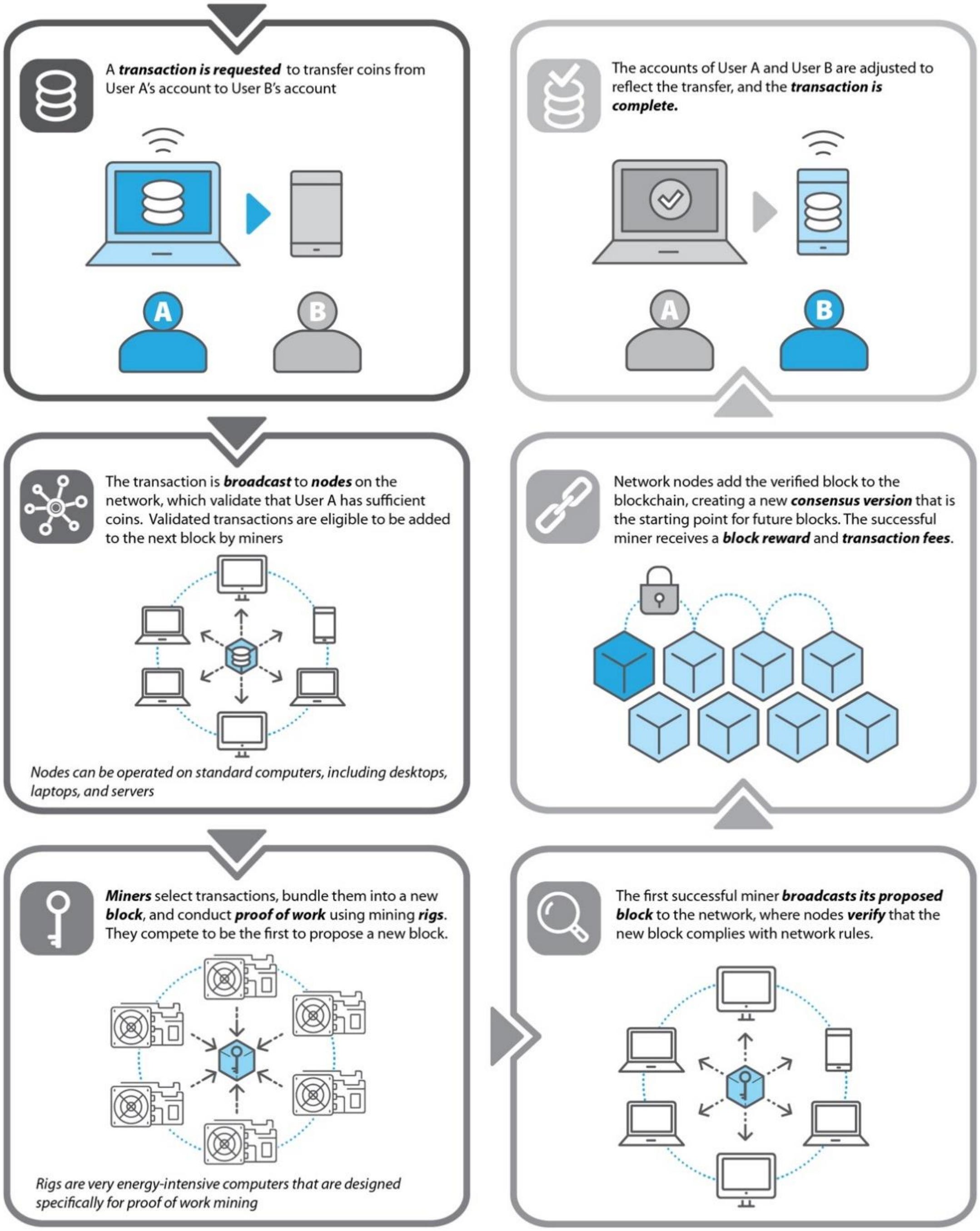
Crypto-Assets Use Digital Cryptography to Maintain Financial Records

Crypto-assets are a type of private sector digital asset that depend on cryptography and DLT, or similar technology. While other assets may involve digital representations of value, assets are only crypto-assets if they rely on a cryptography and DLT, such as blockchain. A distributed ledger is a database in which participants on a common network can record transactions. This ledger provides a mechanism for all users to agree on the ledger entries and transactions — called consensus mechanisms. Different consensus mechanisms enforce different rules for when participants can submit ledger updates. For example, PoW consensus mechanisms,[29] which are currently used for Bitcoin, Ethereum, and other blockchains, require the completion of a computationally-intensive process before a set of transactions, or “block,” is validated and added to the ledger. This ensures that participants are willing to spend significant computational and energy resources in order to add blocks to the ledger. This approach makes it more difficult for malicious participants to force an inaccurate ledger, because they would need to amass a large amount of computing resources and expend a significant amount of energy to achieve a consensus. Participants who submit blocks to the network are known as miners. Miners are incentivized to add blocks to the consensus ledger by performing energy-intensive computations, because they receive compensation in the form of newly minted crypto-assets for adding a block to the blockchain, and they collect fees associated with transactions within the block.[30] Participants confirm the validity of new blocks, adding them to the blockchain ledger, and then store the latest copies of the ledger. Figure 1.1 provides an overview of PoW crypto-asset mining.

As a crypto-asset becomes more valuable, the mining rewards also become more valuable. This attracts more miners and computing resources to solve the cryptographic math problem. As miners dedicate more computing resources to process transactions for a blockchain, the math problem adjusts to become more difficult. This keeps the average time required to find a solution approximately constant.[8] This PoW “economic model” means that a PoW network will generally use more electricity as the crypto-asset’s value (and network) grows, so long as the distribution of the crypto-asset among miners stays constant. The growth in total value of crypto-assets has attracted thousands of miners, who use computers and customized hardware, drawing total electricity amounts comparable to a mid-sized nation or a large metropolitan area.

The most popular alternative to the energy-intensive PoW consensus mechanism is PoS, which is used for networks such as Solana, Cardano, the proposed Ethereum 2.0, and others. In PoS, participants — called validators — typically “stake” an amount of crypto-assets for the opportunity to be chosen to add a new block of transactions to the ledger. The more crypto-assets a validator stakes, or the longer the stake is locked up, the larger the chance of being chosen. Validators who publish inaccurate data or fraudulent transactions risk losing their stake. Dozens of variations exist within the PoS consensus mechanism; variations generally share the principle that trust is inferred by a participant’s willingness to risk their valuable crypto-assets. Because PoS validators rely on risking assets rather than computing power to validate transactions, the electricity use of PoS crypto-assets is much lower than PoW crypto-assets, as shown in Appendix Table A.1.

Beyond PoW and PoS, there are many other types of consensus mechanisms, including but not limited to Proof of Capacity and Practical Byzantine Fault Tolerance, both of which are currently used by existing crypto-assets, as discussed in Appendix Table A.2.[31] Besides electricity usage, there are other issues that affect a crypto-asset’s application and market acceptance, including scalability, security against tampering and falsification, throughput, latency, and decentralization.[32] Every consensus mechanism has strengths and weaknesses. The crypto-asset community has not reached an agreement on what constitutes “best practices” for consensus mechanisms, and other consensus mechanisms with different strengths and weaknesses may emerge. Responsible development of digital assets would encourage consensus mechanisms that minimize energy usage and environmental impacts while maximizing benefits to consumers.



A ***transaction is requested*** to transfer coins from User A's account to User B's account

The transaction is ***broadcast*** to ***nodes*** on the network, which validate that User A has sufficient coins. Validated transactions are eligible to be added to the next block by miners

Nodes can be operated on standard computers, including desktops, laptops, and servers

Miners select transactions, bundle them into a new ***block***, and conduct ***proof of work*** using mining ***rigs***. They compete to be the first to propose a new block.

Rigs are very energy-intensive computers that are designed specifically for proof of work mining

The first successful miner ***broadcasts its proposed block*** to the network, where nodes ***verify*** that the new block complies with network rules.

Network nodes add the verified block to the blockchain, creating a new ***consensus version*** that is the starting point for future blocks. The successful miner receives a ***block reward*** and ***transaction fees***.

The accounts of User A and User B are adjusted to reflect the transfer, and the ***transaction is complete.***

Figure 1.1: Understanding Proof of Work Blockchain in Crypto-Asset Mining. Adapted from Kilroy Blockchain.[33]

2. Crypto-Assets Affect Electricity Usage and the Grid

Digital assets, including crypto-assets, require electricity for generation, ownership, and exchange. Crypto-asset networks use electricity to power four major functions: data storage, computing, cooling, and data communications. Of these, computing uses the vast majority of electricity within crypto-asset networks.[34] Therefore, most studies have focused on estimating the electricity usage of computing devices, including the additional electricity required for cooling.[35] Electricity for cooling can add anywhere from a low percentage (for cool climates) to over 100% of the electricity consumed by the computing equipment itself.[36,37,38]

Electricity Usage Varies for Different Types of Crypto-Assets

The scale and sources of electricity used by computing devices depend on the technology that a crypto-asset uses to ensure security and validity, or its consensus mechanism. For PoS blockchains, computing tasks can be performed by general-purpose computers or servers. The latter can be located in conventional data centers across a network.[39] In PoS blockchains, these computing devices are known as validator nodes (which participate in consensus protocols and produce new blocks) and full nodes (which verify transactions).[40] Due to their high server densities, conventional data centers require additional electricity for onsite cooling. Most data centers in the United States purchase their electricity from the local grid, though some large data center operators are investing in large-scale renewable energy projects to offset their local grid emissions.[41,42] The same is true of international data centers, so the emissions footprints of international PoS blockchain participants depend on local generation sources.

PoW blockchains also use general-purpose nodes to verify transactions, validate consensus protocols, and store consensus copies of the blockchain. However, computing for popular crypto-assets that use PoW blockchains is also performed by specialized semiconductors, based on application-specific integrated circuits (ASICs) contained in "mining rigs" that perform PoW computations.[43,44,45] These mining rigs are often located in "mining" facilities that generally purchase grid electricity and can represent large local electricity loads.[46] These facilities often purchase electricity at lower industrial rates than what residential customers pay, and they sometimes receive special economic incentives, such as energy purchase tax waivers.[47,48,49]

Alternatively, PoW mining operations can build facilities to generate some or all of their own electricity. A mining operation might construct a dedicated solar energy farm with or without energy storage, or might install onsite generators using stranded natural gas.[50] Mining operations can also contract with individual power facilities to connect mining equipment directly to fossil-fired power plants, solar farms, wind farms, hydropower, and other electricity sources.

Table A.3 in the Appendix summarizes estimates of the numbers of computing devices and their typical power needs, for select PoS and PoW blockchain networks in 2021.[51,52] These estimates indicate that each PoS computing device required 10 to 500 times less power than a typical ASIC Bitcoin rig for PoW mining.

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Electricity Usage from Crypto-Asset Activity

While thousands of crypto-assets have been issued globally, published studies have focused on relatively few high market value crypto-assets. The majority of published estimates for crypto-asset electricity usage have focused on Bitcoin, which is estimated to consume the most electricity of any crypto-asset, due to its high market value, popularity among investors and miners, and energy-intensive PoW consensus mechanism. Researchers have also estimated electricity usage for other high market value PoW and PoS crypto-assets, as shown in Appendix Table A.1.

The total power usage of today's crypto-asset networks cannot be directly monitored, because many computing or mining centers do not disclose their location and do not report their electricity usage. Electricity usage can, however, be estimated analytically. Like all uses of electricity, crypto-asset electricity usage is measured in kilowatt-hours (kWh): the use of one kilowatt (kW) of power for one hour. The average U.S. home uses 10,715 kWh per year, or about 900 kWh per month.[53] For reference, all U.S. residential lighting consumes about 59 billion kWh annually, and total annual U.S. electricity consumption in 2021 was 3,930 billion kWh.[54,55]

Total global estimated electricity usage for blockchains that support crypto-assets in 2022 falls into a range of 120 to 240 billion kWh per year.[56] This is equivalent to 0.4% to 0.9% of annual global electricity usage.[57,58] This range is comparable with the annual electricity usage of all conventional (i.e., non crypto-asset) data centers in the world, which consumed between 200 to 250 billion kWh in 2020.[59] However, the electricity usage of crypto-assets can change quickly as miners ramp their activities up or down in response to market value fluctuations, and as they adopt new equipment. As a result, so far in 2022, the estimated range of global crypto-asset electricity usage has fallen as low as 105 to 178, and risen as high as 176 to 305 billion kWh per year, as shown in Appendix Table A.1.[60,61,62,63,64,65,66,67,68]

As of August 2022, two PoW blockchains account for the vast majority of electricity usage: Bitcoin is estimated to account for 60% to 77% and Ethereum is estimated to account for 20% to 39% of the total global crypto-asset electricity usage.[69,70,71,72,73] Annual global electricity usage from the Bitcoin blockchain is estimated to be 90 to 145 billion kWh, with a theoretical range from 40 to 180 billion kWh. Ethereum blockchain electricity usage is estimated to be 23 to 94 billion kWh, with a lower bound of 16 billion kWh. The global electricity usage for analyzed PoS crypto-assets has been estimated as less than 0.28 billion kWh per year, which is less than 0.001% of global electricity usage, and about 0.25% of the lower bound of total global PoW electricity usage. Given the electricity usage estimates, most discussions about crypto-asset electricity usage have focused on PoW applications, particularly Bitcoin.[74,75] There have been growing calls for PoW blockchains to adopt less energy-intensive consensus mechanisms. The most prominent reaction has been Ethereum's promised launch of the "Ethereum 2.0" PoS blockchain.

The United States currently hosts the world's largest Bitcoin mining industry, accounting for around 38% of the global Bitcoin network hashrate, as of August 2022.[76] A hashrate is the total computational power used each second to mine and process PoW blockchains. As the number of miners on a PoW blockchain increases, it becomes more challenging to solve the cryptographic math problem, ultimately increasing the hashrate. Assuming Bitcoin electricity usage is proportional to hashrate,[77] the United States' share of global estimated Bitcoin electricity usage, as of August 15, 2022, would fall into a range of 33 to 55 billion kWh per year, or 0.9% to 1.4% of total U.S. electricity usage in 2021.[78] When the U.S. share of global Ethereum mining is also considered, U.S. PoW mining electricity usage rises to 36 to 66 billion kWh per year, or 0.9% to 1.7% of total annual U.S. electricity usage (see Table A.1). This makes U.S. PoW mining electricity usage comparable with the electricity usage of all U.S. conventional (i.e., non-crypto-asset) data centers, which was most recently estimated at 72 billion kWh per year.[79] Figure 2.1 demonstrates that crypto-asset electricity usage is also similar to electricity consumption for some countries, states, or critical energy services.

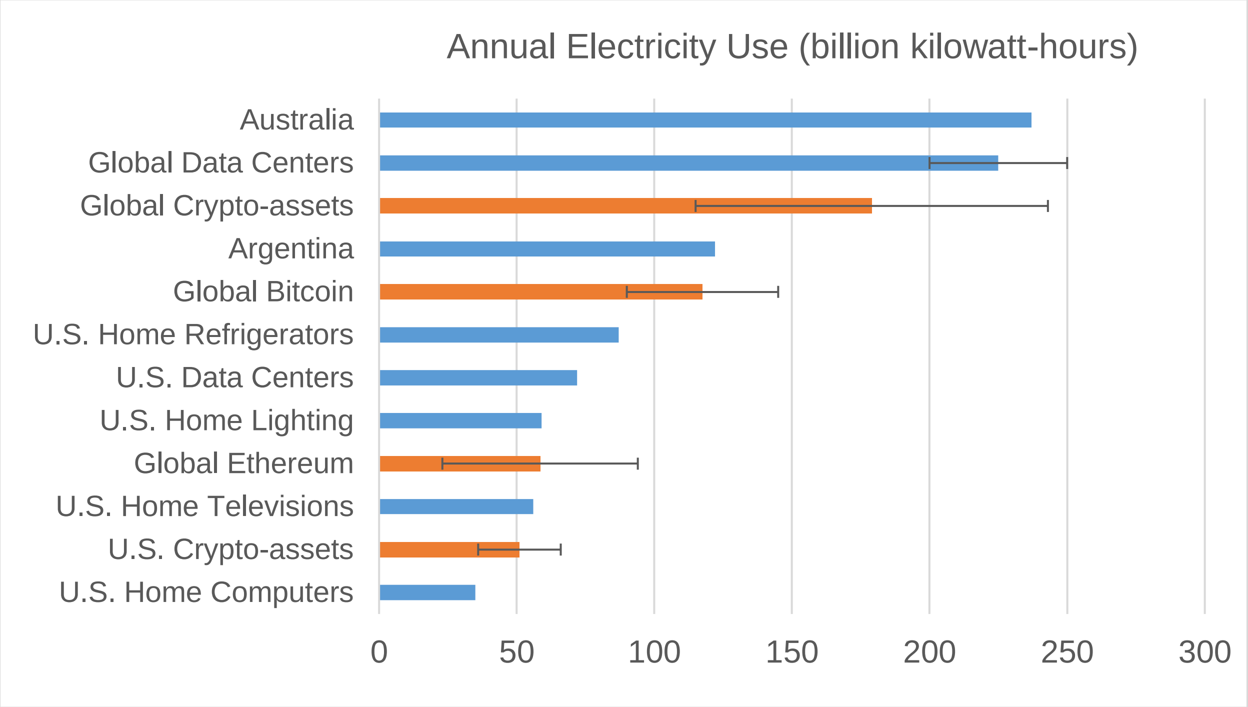


Figure 2.1: Comparison of Annual Electricity Use of Several Examples and the Best Estimates for Crypto-assets, as of August 2022, with error bars representing the best range of values.[80,81]

Given the differences in methodologies and the dates to which existing electricity usage estimates apply, electricity estimates must be interpreted with caution. The Bitcoin blockchain's estimated electricity usage rose steadily as Bitcoin's market value and network hashrates increased — conditions that may occur for other PoW blockchains that support crypto-assets. Additionally, the differences between upper and lower bound estimates have increased over time, reflecting uncertainties about the types of mining rigs that may be profitably deployed when crypto-assets experience higher market values. While large ranges can give policymakers indications of how large PoW electricity usage could be, they also suggest a need for miners to report their actual electricity usage to reduce uncertainties. Also, for time series studies, there can be variation in the estimated day-to-day power usage,[82] due to crypto-asset market value fluctuations. Market dynamics can quickly render any published estimate out-of-date.

* * *

Comparison with Other Financial Transactions

Crypto-assets can be used for investment or speculative purposes, as a means of payment, or as a store of wealth. While a credit card transaction only accounts for a single payment between parties, multiple Bitcoin transactions can be bundled together into one “on-chain” transaction, which can combine different types of financial activities into a single posted blockchain transaction. For example, when someone buys or sells bitcoin, or buys a coffee with bitcoin, these are each recorded as a transfer of bitcoins from one address to another, and a record of that transfer is added to the next block along with other transactions. A block on the Bitcoin blockchain typically contains 1,000-2,000 transactions, with the amount of transactions per block changing daily.[83] The average time to solve the PoW math problem and record a Bitcoin block to the ledger is about 10 minutes, so 52,560 blocks are added to the Bitcoin blockchain per year. Bitcoin's current global electricity consumption is 90 to 140 billion kWh per year. This requires about 1.7 to 2.7 million kWh per block, which can be further divided to estimate kWh per on-chain transaction. This is only an approximate estimate. With Bitcoin, as with other crypto-asset transactions, centralized crypto-asset trading platforms typically use off-chain transactions, and use on-chain transactions for certain activity, for instance, when sending crypto-assets to a participant outside of the platform. The result is crypto-asset platforms only send a portion of transactions to a blockchain, and electricity usage from off-chain activity is unlikely to be captured in estimates. Factors such as these provide challenges in estimating actual total per-transaction electricity usage compared to other financial services.

The total number of on-chain crypto-asset transactions is currently small compared to those of traditional financial services. In 2020, Bitcoin and Ethereum together accounted for roughly 460 million reported on-chain transactions.[84,85] That same year, Visa, MasterCard, and American Express collectively processed an estimated 310 billion credit card payment transactions.[86] DLT, including Bitcoin’s and Ethereum's blockchains, constitutes complete payment systems and allows for real-time gross settlement between parties. Credit card merchants, in comparison, need formal banking relationships to settle transactions, because a transaction only authorizes payment, and does not settle payments. For this reason, there is a fundamental difference between a digital asset transaction and a credit card transaction.

Noting direct comparisons are complicated, Visa, MasterCard, and American Express combined reported around 0.5 billion kWh of electricity usage in 2020,[87] inclusive of all operations, in addition to electronic payments.[88,89,90] In other words, these three entities consumed less than 1% of the electricity that Bitcoin and Ethereum used that same year,[91] despite processing many times the number of on-chain transactions and supporting their broader corporate operations. Responsible development of digital assets includes ensuring operations with dramatically lower energy intensity, as digital assets are adopted.

Crypto-Asset Mining Can Affect Electricity Consumers and the Grid

The electricity system is critical infrastructure for human health, the economy, and U.S. national security. It is also the backbone of a future U.S. clean energy economy, as electrification will increasingly displace fossil-fueled vehicles, buildings, and some industrial processes. The United

States will need to accelerate the electrification of end uses in order to meet its climate objectives. The 2020s are a decisive decade for climate action in the United States, and up to 100 GW of clean electricity capacity needs to be added to the grid every year to meet the demand of these newly electrified end uses.[92] At the same time, electricity infrastructure is under stress from today's demands and climate-driven weather extremes,[93] and requires massive reinvestment. Twice as many power outages have occurred in the last six years in comparison to the previous six years, and reliability will have to increase in order to accommodate new electricity demands.[94] Electricity infrastructure that was designed for the climate of the 20th century now has to withstand hotter temperatures, more intense storms, and other extreme conditions exacerbated by climate change, which strain the grid and can reduce the amount of electricity provided when consumers need it most.[95] The United States requires a reliable, affordable, clean, equitable, and climate-ready electricity system. New demands on the system must help, not hinder, our nation's climate objectives.

In most electricity grids, renewables with low fuel costs and nuclear plants are dispatched first to meet electrical loads. Flexible resources with higher fuel costs, such as natural gas or coal power plants, are then dispatched to follow load fluctuations through the day. As electricity demand increases from crypto-asset mining, more natural gas and coal power plants are dispatched by electricity system operators. These power plants generally cost more and pollute more than the average grid electricity, with the difference between average emissions and marginal emissions widening.[96]

Crypto-asset mining operations typically have high load factors: they use power nearly constantly. When these facilities continue to operate through peak demand periods, they stress the power infrastructure, which can affect equipment life, cause blackouts for other customers, and create fire hazards.[97] The Public Utility District of Grant County, Washington adopted a rate class for crypto-asset miners to recover incremental costs associated with meeting electricity demand from mining.[98] The Public Utility District of Benton County, Washington also adopted a policy for crypto-asset customers, citing concerns about the distribution system safety and reliability.[99]

The increased electricity demand from crypto-asset mining can also push up power prices for local consumers. Crypto-asset mining in upstate New York increased annual household electric bills by $82 and annual small business electric bills by $164, with net total losses from local consumers and businesses estimated to be $179 million from 2016-2018.[100] In 2018, The New York Municipal Power Authority created a new tariff in 2018 for high-volume data processing for crypto-assets to raise the cost of mining.[101] Plattsburgh, NY enacted an 18-month long moratorium on mining operations after community members and businesses complained of high energy bills and noise. Mining could also result in cost-shifting to local electricity customers, who will bear the risk if mining operations move to different places when conditions change. This could leave local customers to pay for unpaid infrastructure upgrades for mining operations.

Many crypto-asset miners have moved their operations to Texas. The Electricity Reliability Council of Texas (ERCOT) is the grid system operator for the majority of Texas, and has a peak summer electricity demand of about 76 gigawatts (GW), and current crypto-asset mining activity of about 2 GW. ERCOT has about 17 GW of crypto-asset facilities that are in the process of connecting to the grid, with an expected 5 to 6 GW of new demand in the next 12 to 15 months (equivalent to the power demand of the city of Houston). ERCOT may also see an additional 25 GW over the next decade.[102] While many of these projects may not be completed, the prospect of up to 25 GW of new electricity demand from crypto-asset mining — equivalent to a third of existing peak electricity demand in Texas — raises potential challenges for maintaining electricity reliability, especially with rising power demands and extreme temperatures over recent years.

Crypto-asset mining operations can quickly decrease the amount of electricity used by scaling back or switching off mining rigs. Bitcoin miners can participate in utility and grid operator programs that pay major electricity users to decrease consumptions during times of peak grid stress, or to balance supply and demand — a process called demand response. On July 11, 2022, high temperatures and high projected electricity demand caused ERCOT to declare a grid emergency event, and bitcoin miners using 1 GW of power reportedly responded to ERCOT's demand response request and reduced mining power usage.[103] In all of July 2022, a single publicly traded Bitcoin miner who operates a facility in Texas earned $9.5 million from the demand response program from the Texas grid, which was more than the value of the 318 bitcoins the facility produced in the same month.[104] Flexible electricity demand, rapid demand response, and the provision of electricity ancillary services are essential attributes of a decarbonized electricity grid comprised of variable renewable electricity such as wind and solar. Crypto-asset mining's flexibility to ramp up and down could contribute to these needed rapid response services. Increased electricity demands from crypto-asset mining also increase the overall peak level of grid demand. While reducing this peak during a grid emergency is valuable, the increased peak is often why demand response is necessary, establishing misaligned incentives between crypto-asset miners and grid operators. Full transparency of demand response participation and payments by crypto-asset miners and other demand response participants are essential. Transparency reduces the incentive for rent-seeking and gaming, protects local electricity consumers, and can improve electricity reliability.[105]

Internationally, legislation and regulation have addressed environmental concerns about crypto-asset activity. The European Commission's pending Markets in Crypto-Assets legislation will likely require increased environmental and climate impact information and, within two years, the introduction of mandatory minimum sustainability standards for consensus mechanisms.[106] In China, the incompatibility of large-scale Bitcoin mining with the country's environmental goals has been cited as one several reasons that the government banned crypto-asset transactions in 2021.[107]

Future Crypto-Asset Electricity Usage Projections Are Uncertain

Energy usage projections are estimated by energy systems models that capture the relationships between demands for services, technological efficiencies, energy supply options and prices, and changes in macroeconomic factors such as population size and economic productivity over time.[108] However, existing energy systems models do not adequately represent digital technologies such as data centers and telecommunications networks, let alone crypto-asset and blockchain networks. This is a well-known modeling gap that inhibits robust energy projections for digital systems.[109] Future projections determined by other estimation methods require forecasting network hashrates and profitable mining rig efficiencies, which are closely interrelated and further influenced by a crypto-asset's market value and prevailing electricity prices.

There is also considerable uncertainty about the number of crypto-assets that will emerge, how popular they will become, and which consensus mechanisms they will adopt. All of these factors will affect electricity demand. The risks associated with growth of PoS or other less energy-intensive network are considerably lower than the risks associated with PoW network growth. Figure 2.2 plots historical trends in the market value and network hashrates of the Bitcoin network between August 1, 2016 to August 24, 2022.[110] While the network hashrate dropped in response to the Bitcoin market value slump between July and September 2021, a similar correlation between market value and network hashrate has not been observed in the current market value slump that began in late 2021. Thus, projections of future network hashrates on the basis of forecasted coin market values come with significant uncertainties. Extrapolating current conditions into the future should be avoided, as these uncertainties and key system variables can change. In the past, simple extrapolations have often yielded unrealistic energy demand predictions for complex and evolving information technology systems like those that comprise blockchains.[111]

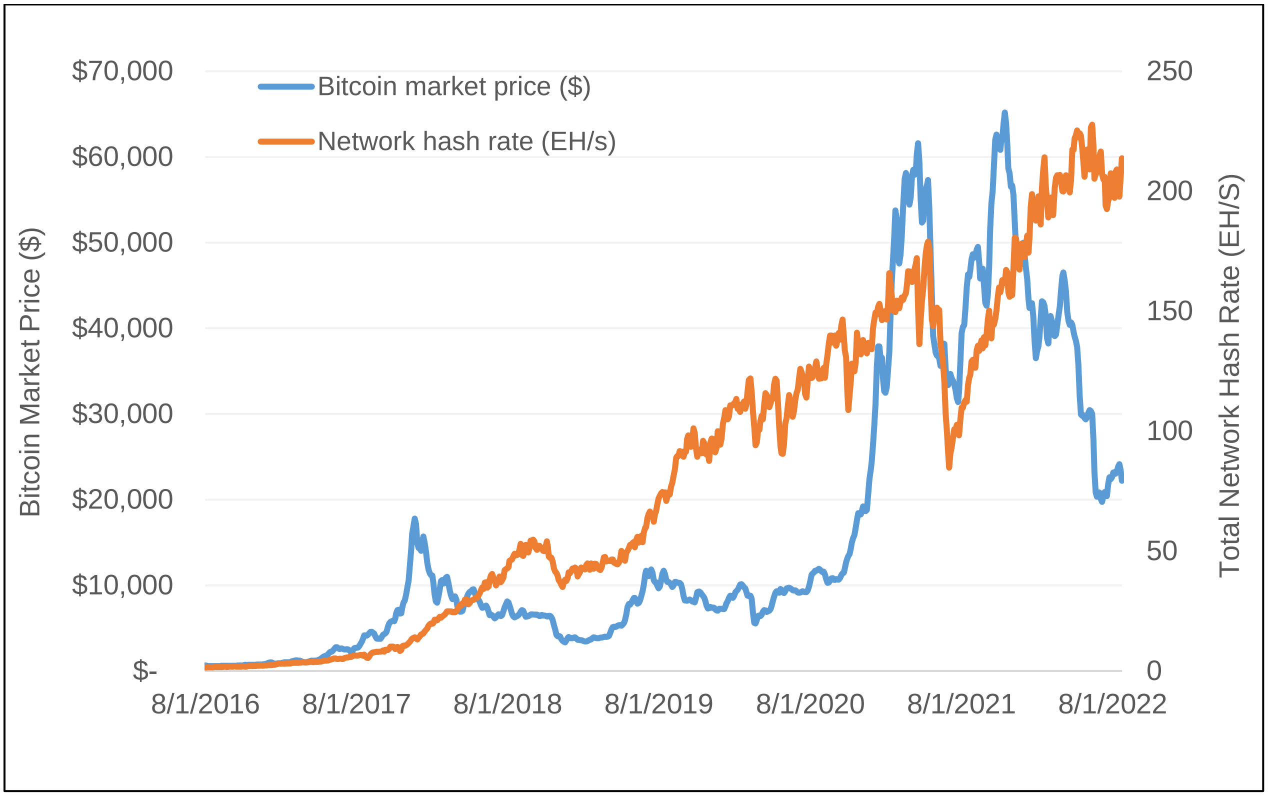


Figure 2.2: Historical trends in Bitcoin market value and network hashrate (Exahash/second)[112]

Between August 2016 and July 2022, the average estimated deployed rig energy intensity decreased by around 85% due to computational efficiency improvements.[113,114] Over the same time period, network hashrates increased by over 14000%, leading to a 2000% rise in estimated network electricity usage.[115] This increase illustrates how, historically, mining rig efficiency improvements have been negated by rising hashrates as mining competition has increased. However, the future relationship between network hashrates and deployed mining rig efficiencies is uncertain. This is due to unknowns regarding the remaining computational efficiency improvement potential for mining rigs and, for certain crypto-assets like Bitcoin, how mining incentives will be affected by future reductions to the rewards for mining, which may limit the growth of Bitcoin electricity usage. These uncertainties, and the ability for crypto-asset electricity usage to grow rapidly, demonstrate the need to obtain better data to understand and monitor electricity usage from crypto-assets.

3. Crypto-Assets Result in Greenhouse Gas Emissions and Other Environmental Impacts

Crypto-Asset Mining Using Grid Electricity Generates Greenhouse Gas Emissions — Unless Mining Uses Clean Energy

Crypto-asset mining produces GHG emissions and exacerbates climate change primarily by burning coal, natural gas, or other fossil fuels to generate electricity in 1) an onsite dedicated power plant, 2) purchasing electricity from the power grid, and/or 3) producing and disposing of computers and mining infrastructure, and production of power plant fuels and infrastructure. These three categories correspond to scopes 1, 2, and 3 of the Greenhouse Gas Protocol,[116] a voluntary industry standard.

Current estimates of carbon dioxide (CO_2) emissions from crypto-asset mining in 2022 are 110 to 170 (or 140 ± 30) million metric tons, globally, and about 25 to 50 million metric tons in the United States.[117,118,119] This represents 0.2% to 0.3% of global emissions and 0.4% to 0.8% of U.S. emissions, respectively. Assessing emissions from crypto-assets is complex; consequently, the estimates are uncertain.

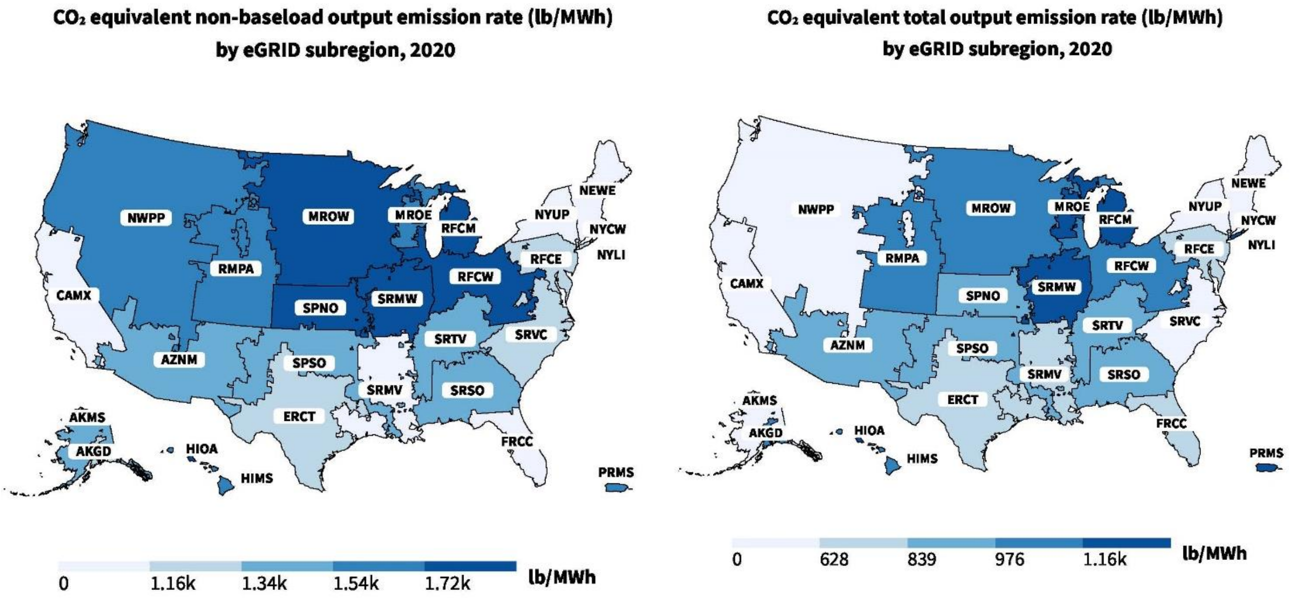
Because the electricity consumption of crypto-asset mining can fluctuate rapidly, and country shares of mining fluctuate depending on prices and activity, the associated GHGs from this electricity usage also fluctuate. Using economic and location-based estimates of mining activity, and data on country-level GHG intensity of electricity, researchers have estimated ranges of GHG emissions associated with major crypto-assets.[120,121]

Global crypto-asset mining emissions, at a rate of 140 Mt CO_2/y, are greater than the emissions of many individual countries, and equivalent to the global emissions from all barges, tankers, and other ships on inland waterways.[122] Bitcoin alone generates approximately two-thirds of global crypto-asset GHG emissions.[123,124,125,126] Bitcoin emissions have increased rapidly from a range of 2 to 16 Mt CO_2/y in 2017[127,128,129] to 100 ± 20 Mt CO_2/y from May 30 to June 16, 2022,[130,131,132] an increase of approximately 10 times in five years.

Estimates of the global energy mix used for crypto-asset mining have varied, due to the changing locations of mining operations and annual water flow cycles that affect hydroelectric generation. From September 2019 to August 2021, an average of 30% of the electricity used by Bitcoin came from hydroelectric, solar, wind, and other renewable sources.[133] Hydropower in China provided a majority of renewable electricity for Bitcoin during this period. Following China's ban on crypto-asset mining in September 2021, the renewable energy used for Bitcoin has decreased. Consequently, the estimated average carbon intensity of electricity used for Bitcoin mining increased from 480 to 570 grams of CO_2 per kilowatt-hour from 2018 to 2021.[134]

The GHG emissions intensity of electricity production has fallen by more than 33% in the United States since 2005, with average electricity GHG emissions at 373 g/kWh in 2020.[135] This emissions rate is lower than the emissions rate of natural gas power plants (412 g/kWh) and about 63% lower than U.S. coal plants (1011 g/kWh).[136] About 61% of U.S. electricity generation in 2021 was from fossil fuels (38% natural gas, 22% coal, 1.3% other). The remaining 39% of U.S. electricity is generated by nuclear (18.9%) and renewables (9.2% wind, 6.3% hydropower, 2.8% solar, 1.3% biomass, and 0.4% geothermal).[137] Demand for electricity in the United States is met by power plants, energy storage assets, and grid management tools increasing or decreasing the amount of available electricity, as customer demand changes.

Regional electricity system operators, which are often spread over multiple states, generally balance electricity supply and demand, and trade electricity with neighboring grid operators.[138,139] An authoritative and accessible source of regional electricity emissions information is the Emissions & Generation Resource Integrated Database (eGRID), produced by the EPA.[140] The GHG emissions from electricity generation vary by region. The carbon intensity of the central Great Plains is about 700 g/kWh due to relatively more coal power, producing nearly three times the CO_2-equivalent emissions per non-baseload kWh of electricity of California (234 g/kWh). These are all average emissions rates, and new electricity demand from crypto-assets affects the sources used for electricity in both the near-term, generally requiring the use of non-baseload emissions factors, and in the long-term, as the grid composition changes.



CO_2 equivalent non-baseload output emission rate (lb/MWh) by eGRID subregion, 2020

CO_2 equivalent total output emission rate (lb/MWh) by eGRID subregion, 2020

Figure 3.1. U.S. GHG intensity of electricity varies by region, for both non-baseload (left) and average electricity (right).[141]

According to a published study, in 2021, U.S. electricity generation for mining crypto-assets with the largest market capitalizations (Bitcoin, Ethereum, and Dogecoin) generated GHGs at a rate of approximately 15 Mt CO_2/year.[142] One year of U.S. crypto-asset GHG emissions at this rate is equivalent to the annual emissions from more than 3 million gasoline-powered cars for a year of average U.S. travel.[143] Since then, crypto-asset mining activity has increased in the United States, which now hosts more than a third of global Bitcoin activity.

U.S. electricity consumption to mine Bitcoin has increased from 8 to 11 billion kWh in early 2021, to 33 to 55 billion kWh in mid-2022.[144] Using EPA eGRID U.S. non-baseload GHG emissions, 33 to 55 billion kilowatt-hours for U.S. Bitcoin mining alone would generate about 21 to 35 Mt CO_2/y. To provide context for how regional U.S. electricity mixes affect GHG emissions, if all U.S. crypto-asset mining for the two largest crypto-assets (Bitcoin and Ethereum) occurred at 2022 rates in a single U.S. eGRID sub-region, an average of 42 billion kWh/y of electricity would generate GHG emissions ranging from a low of 17 Mt CO_2/y in upstate New York to 38 Mt CO_2/y in the central Great Plains. When the U.S. share of total global crypto-asset activity is considered, emissions estimates range from 25 to 50 Mt CO_2/y. Using average emissions rates instead of non-baseload rates, emissions would be lower by about half. As the grid decarbonizes, average emissions intensity of electricity will continue to decline. The uncertainty in the estimates of GHG emissions from crypto-assets, and the potential for future growth, are reasons for better, timely data from stakeholders on electricity usage and emissions.

In Montana,[145,146] New York,[147] Pennsylvania,[148] Indiana,[149,150,151] and elsewhere, media has reported cases where crypto-asset companies have reversed closure plans for fossil-fueled power plants, or have restarted previously closed electric plants.[152,153] Restarting coal and other fossil fuel plants erodes some of the progress that the United States has made in reducing GHG emissions.[154,155]

In addition to the emissions from electricity generation, the scope 3 emissions of crypto-asset operations include GHGs emitted in production, transportation, maintenance, and disposal over the life cycle of computers, buildings, motor vehicles, and other equipment. Mining minerals and producing steel and other materials for computing equipment also emit GHGs, but the majority of emissions associated with crypto-assets come from electricity generation to run crypto-asset mines, totaling about 79% to 99% of life cycle emissions.[156,157]

Crypto-Asset Mining Can Be Powered by Stranded Methane and Renewables

The crypto-asset industry can potentially use stranded methane gas, which is the principal component of natural gas, to generate electricity for mining. Methane gas is produced during natural gas drilling and transmission, and by oil wells, landfills, sewage treatment, and agricultural processes. Methane is a potent GHG that can result in 27 to 30 times the global warming potential of CO_2 over a 100-year time frame, and is about 80 times as powerful as CO_2 over a 20-year timeframe.[158] Reducing methane emissions can slow near-term climate warming, which is why the Biden-Harris Administration released the U.S. methane emissions reduction action plan in 2021.[159]

Venting and flaring methane at oil and natural gas wells wastes 4% of global methane production.[160] In 2021, venting and flaring methane emitted the equivalent of 400 million metric tons of CO_2,[161] representing about 0.7% of global GHG emissions.[162] This methane is vented or flared, because of the high cost of constructing permanent pipelines or electricity transmission that could transport the methane or its potential electricity generation from remote oil and gas operations to end-users, or because of the high cost of installing equipment on older landfills. Crypto-asset companies are now exploring ways to use electricity generation from vented and flared methane at oil and gas wells and at landfills.

While the EPA and the Department of the Interior have proposed new rules to reduce methane for oil and natural gas operations, crypto-asset mining operations that capture vented methane to produce electricity can yield positive results for the climate, by converting the potent methane to CO_2 during combustion. Mining operations that replace existing methane flares would not likely affect CO_2 emissions, since this methane would otherwise be flared and converted to CO_2. Mining operations, though, could potentially be more reliable and more efficient at converting methane to CO_2. While such operations can reduce wasted methane, another option is low-cost recovery of methane using existing vapor capture technologies at oil and gas wells, which can reduce global methane emissions up to 50% by 2030.[163]

Climate policy aligned with achieving net-zero emissions would have zero methane venting and zero methane flaring. A combination of regulation and technological innovation can help realize this vision. Crypto-asset mining that installs equipment to use vented methane to generate electricity for operations is more likely to help rather than hinder U.S. climate objectives. However, unless the CO_2 is captured and stored, using vented methane at oil and gas wells will still generate CO_2 emissions and contribute to climate change. Using vented or flared methane for crypto-asset mining must also be assessed against other uses for this methane, such as hydrogen production or transporting the methane via pipeline to end-users.

There are two primary ways crypto-asset mining using grid electricity would result in zero direct GHG emissions: 1) constructing or contracting for new clean electricity sources to power mining, or 2) using existing renewable electricity that would otherwise be curtailed by the grid. When a crypto-asset mine purchases electricity from existing renewable sources, it displaces the GHG emissions in the near-term, shifting users of renewable sources to fossil fuel sources. This is because coal and natural gas often supply electricity generation for each additional unit of electricity demanded in the United States. As the amount of renewable sources is held constant, but electricity demand increases, additional fossil power will likely be dispatched.[164] This displacement results in no net change or in increases in total global emissions through a process called leakage.[165,166,167,168,169,170,171]

If a crypto-asset operation builds or contracts new zero-carbon energy capacity, and matches both the annual electricity usage and temporal profile to the new zero-carbon electricity generated, then the direct mining activity would be emissions-free, since the mine would use all of the new zero-carbon generation it provides. To help U.S. climate objectives, industries could volunteer or be required to build zero-carbon energy capacity that produces more electricity than the crypto-asset mine requires, selling excess clean energy back to the grid.

In some areas of the United States, there is not enough demand or transmission capacity to use peak levels of generated renewables, and wind or solar generators temporarily reduce or eliminate output in a process called curtailment. This is wasted renewable electricity, because if sufficient transmission capacity or demand existed during these times, then generators would produce and sell renewable electricity. In 2019, 2.6% of wind power in the United States was curtailed, with the highest amount occurring in the Great Plains states. In Texas, 5% of annual solar power was curtailed, and in California, 2.4% of solar was curtailed.[172] Using curtailed electricity can provide additional revenue to renewables developers and incentivize the construction of additional renewable energy capacity. However, it can also reduce the financial incentives to construct transmission from these renewables to existing users, or reduce the incentives to store excess renewable electricity to use when demand is higher. In addition, crypto-asset miners would not be likely to operate only during periods of curtailment, requiring consumption of grid electricity at all other times.

Environmental Impacts Include Air and Water Pollution, Noise, and Electronic Waste

Crypto-asset mining largely uses electricity purchased from the grid. The electricity generated at power plants to power crypto-asset mining and for all uses of electricity can damage the environment and human health with air pollution from fossil fuel burning, water withdrawals and thermal water pollution from power plant cooling, other water pollution, solid waste from fossil fuel combustion, land degradation from exploration and mining, and life cycle impacts of fuel cycles and power plant construction.

Crypto-asset mining raises environmental justice concerns because it can create disproportionately adverse public health and environmental burdens for communities of color, Indigenous communities, and low-income communities.[173,174] For example, within the ancestral homeland of the Onondaga Nation in upstate New York, a Bitcoin mining operation re-started the previously-closed Greenidge coal-fired power plant. With the support of the Onondaga Nation, the New York State Department of Environmental Conservation denied Greenidge's application for a renewal of its Clean Air Act Title V operating permit on June 30, 2022, because it violated the state GHG emission reduction law.[175] Restarting previously closed coal-fired plants for new crypto-asset mines erodes some of the previous improvements in air quality. Because underserved communities are already burdened by pollution and underinvestment in infrastructure, the additional impacts of crypto-asset mining can create cumulative burdens.

Crypto-asset mining operations also affect the environment through local noise and water impacts of mining operations, and through air and other pollution from any direct use of fossil-fired electricity. Similar to data centers, the groups of computers at crypto-asset mining operations generate substantial heat. Many crypto-asset mining facilities must use air cooling or liquid cooling to keep computers within acceptable temperature ranges. In standard computer data centers, a single, typical 10 kW rack of servers will require around 63,000 gallons of potable water per year for air cooling[176] — an amount comparable to the average indoor water use of an individual U.S. household each year.[177] When liquid cooling is utilized — which involves immersing the computers in liquid baths or removing heat directly from their computing chips via closed liquid loops — facility water requirements can be substantially reduced.[178]

Fossil-fired electricity that directly powers mining operations also impacts local water. At thermal power plants with traditional once-through cooling systems, water is withdrawn from rivers or lakes, and both the withdrawal process and the warmed water released back into the environment (including chemicals used to clean the cooling system) can harm fish and wildlife, and can negatively impact recreation and water quality. Heated effluents lower the solubility of oxygen in the water, increasing the metabolic rate of aquatic organisms, which further reduces dissolved oxygen as respiration increases. Rising water temperatures can also contribute to overpopulation of the organisms that form algal blooms, leading to toxic conditions in local waterways. Other water pollution results from fossil-fired electricity generation as well as the production of coal and natural gas for power plants.

Air-cooled mining computers contain high-velocity fans that can generate noise pollution. While there is a lack of published scientific research on fan noise, numerous media reports describe the loud, irritating, and nearly continuous noise caused by fans at crypto-asset mining centers.[179,180,181,182] Noise pollution can induce physical and mental stress, hearing loss, sleep loss, and cardiovascular disorders.[183] Noise can also reduce property values.[184] In general, noise pollution from industry, road traffic, and airports is higher in communities of color and other underserved populations.[185]

Finally, discarded computers, circuit boards, cables, and other electronic waste from crypto-asset mining contribute to electronic waste. Without standards and enforcement of proper disposal methods, electronic waste can cause air and water pollution, expose workers to toxic substances, and damage public health. Lead and mercury are the most common toxic elements in electronic waste.[186] Additionally, valuable elements, including cobalt, indium, and gold are discarded, impeding a valuable recycling and circular economy opportunity. In May 2021, Bitcoin mining activity produced electronic waste at an estimated rate of 31,000 tons per year,[187] increasing by June 2022 to 35,000 tons per year,[188] equivalent to the annual electronic waste generation of the Netherlands.[189] A phenomenon driving the disposal of ASICs, the dedicated computer units for PoW crypto-asset processing, is a pace of innovations that can double computer processing speeds every one and a half years.[190] Currently, ASICs cannot be used for any other purpose, so companies often discard, sell, or reduce the use of older generations of ASICs after approximately one year and four months.[191] This is shorter than standard data center servers, which last three to five years.[192]

Electronic waste can be reduced by using certified electronics recyclers.[193] Currently, two accredited certification standards exist: the Responsible Recycling Standard for Electronics Recyclers and the e-Stewards Standard for Responsible Recycling and Reuse of Electronic Equipment. Both certification programs advance best management practices and are based on strong environmental standards that maximize reuse and recycling, minimize hazards to human health and the environment, ensure safe management of materials by downstream handlers, and require destruction of all data on used electronics. Recycling electronic waste presents an opportunity for the recovery of critical minerals, in addition to reducing GHG emissions and limiting disposal. When reuse or recycling is not possible, responsible disposal of electronic waste includes accurately characterizing the waste and sending it to proper permitted disposal sites.

4. Emerging Digital Asset Technologies Could Support Climate Monitoring or Mitigation

Executive Order 14067 calls for a discussion of the potential uses of blockchain that could support technologies for monitoring or mitigating climate impacts. Responsible development of blockchain and DLT would encourage innovation in applications, while reducing energy intensity, minimizing total environmental damages, improving environmental justice, and helping the United States meet its climate commitments. This section introduces some potential applications in this area, as well as opportunities for further innovation.

Blockchains and Distributed Ledgers in Environmental Markets

Generally, environmental markets use market-based approaches to address negative externalities, which occur when consumption or production causes a harmful effect or cost to a third party. In the consumption or degradation of environmental and natural resources, negative externalities include water and air pollution, decreased biodiversity, climate change, ecosystem threats, and economic impacts. These negative impacts can be uncertain in their scope and timing, can play out over many years, and can be difficult to account for using traditional accounting measures.[194] A key priority of this Administration is to effectively address negative externalities of climate and other environmental pollution in communities that are already overburdened and underserved.[195]

Carbon markets aim to reduce GHG emissions by trading and using carbon allowances and/or carbon credits. A carbon allowance is a tradeable instrument that authorizes a source to emit a set amount of GHGs (e.g., one metric ton of CO_2) pursuant to a regulatory program. A carbon credit is a tradeable instrument representing one metric ton of GHGs reduced or removed from the atmosphere. Regulatory markets, also known as “compliance markets,” have typically been “cap-and-trade” programs.[196] The creation of allowances, plus a cap that can be ratcheted down, provide a pathway for lowering emissions from regulated sources. Some compliance markets allow regulated entities to use carbon credits in limited quantities as a supplement to allowances, but markets for carbon credits can also occur outside of regulation. These are known as voluntary carbon markets (VCMs). In VCMs, the current primary driver of demand is the corporations that are seeking to meet voluntary climate neutral commitments or other corporate sustainability commitments.

As with other markets, environmental markets depend on robust market infrastructure to enable market participants to transact with confidence. A robust market infrastructure should include mechanisms for trade execution; payments, clearing, and settlement; record-keeping; and security. Carbon markets are designed to ensure that carbon allowances and credits can be trusted to deliver the promised emissions reductions and climate objectives.

Blockchain and DLT may have a role to play in enhancing market infrastructure for a range of markets, including environmental markets. The rationale for replacing existing market infrastructure technologies with DLT will depend on the context in specific markets, including switching costs. In environmental markets specifically, those who propose to adopt DLT should ensure that the environmental benefits are clear, relative to the environmental footprint of existing market infrastructure technologies. DLT adopters should also ensure that the environmental footprint of the DLT does not negate the benefit of the associated environmental market products.

To date, administrators of compliance markets have not adopted blockchain or DLT. A central authority regulates and controls the process of issuing and surrendering carbon allowances. Covered entities have regulatory requirements to ensure the integrity of emissions reporting, and to ensure that emissions reductions are achieved. DLTs are designed to solve issues of decentralization. Because compliance markets are centralized, there may not be clear advantages for DLT in compliance markets.

In VCMs, some uses of DLT are emerging, though it is not yet clear if they reflect an improvement over existing market infrastructure. Crucially, some stakeholders have raised concerns that existing carbon credits may not represent additional, permanent reductions in GHG emissions. Institutions and market actors should ensure that credit-generating projects result in emissions reductions or removal. A blockchain-based scheme could undermine efforts to improve credit quality, if, for instance, credits were tokenized and the underlying quality of credits became more difficult to discern. Moreover, there is a growing consensus that carbon credits are a “complementary tool” that should not delay or be a substitute for viable emissions reductions within a company’s own activities. Thus, ensuring the integrity of VCMs requires understanding the circumstances under which carbon credits are retired by companies. To the extent blockchain-based trading hides the identity of the end-user of carbon credits, they would be antithetical to high-integrity VCMs and broader efforts to promote progress towards net-zero objectives. Finally, while blockchain is often promoted as enhancing trust, it is often the integrity of the underlying carbon reduction or removal project that is questioned, not the counterparty’s likelihood of completing the trade. This issue of trust in VCMs is not the trust issue that blockchain or distributed ledgers solve.

Ultimately, blockchain and DLT may have potential applications for environmental markets, just like these technologies have in any other market, provided they abide by established market rules. The challenge these markets face is verifying that the standards ensure that the particular market advances the desired environmental objective. This equates to verification of physical activities and outcomes against those standards and, as appropriate, enforcement of standards. These elements of successful environmental markets extend beyond the functionality and purported trust-enhancing features provided by blockchain or any other database or cryptographic technology. Once again, the challenges relate to verification of the real asset, not to trading of the title to the asset.

For market and trading infrastructure, the potential use cases for blockchain in carbon markets track existing market functions, and their adoption will depend on whether blockchain can offer an improvement over existing technologies in cost, speed, and security, without causing additional environmental harms. Responsible introduction of DLT into carbon markets would also assess environmental justice to determine how conditions for affected communities are made worse or improved as a result.

Blockchain as Enabling Technology for Distributed Energy Resources

Emerging uses of blockchain technologies for energy management include enabling California's Flex Alert system. This system enables the electricity grid operator to push out requests for energy conservation during a grid emergency, securely interact with customers, and understand participation rates while maintaining customer anonymity.[197,198] Beyond information exchanges, smart grid technology[199] has the potential to harness the services of millions of distributed energy resources (DERs), such as electric vehicles, fuel cells, residential and commercial battery systems, and solar power systems, to enhance grid reliability. DLT could potentially serve as the digital ledger for the registration, authentication, and participation of these DERs in a smart grid, enabling flexible grid operations as more variable renewables are adopted. As with any new and still-maturing innovative technology, the ultimate utility of DLT in the electricity sector is unknown. Today, the electricity grid and markets are highly centralized systems, where a small number of providers sell electricity to a large number of consumers. This dynamic could change in the decade ahead, as more electricity consumers also become providers. DLT-supported innovation could help digitize, automate, and decentralize the operation of the electricity grid.[200] A key feature of mature DLT is the ability to automatically negotiate and execute an agreement, a process known as smart contracting.[201] The automated and distributed nature of DLT makes it a candidate for supporting the evolving clean electricity marketplace with increasing numbers of DER assets.

More than 100 million new storage devices will be connected to the grid by 2040. All of these devices could operate as both electricity consumers and providers, if they can be coordinated. Efficient and secure market participation of 100 million DERs will require digital control of the electricity grid and more autonomous and distributed control than is possible with today's technologies.[202] Every DER is a potential physical-cyber security risk that could maliciously damage the physical grid, hardware systems, software systems, and data. Any introduction of DLT into this system should require enhanced security.

Additionally, in a more diverse system of providers and consumers, DLT could increase reliability. DLT could enable verification by allowing the grid-operators and aggregators to audit, in real-time, the services provided by every DER within the pool through analysis of the tamper-resistant distributed ledger. This is important because grid-operators will require verification that aggregators are providing the contracted services. In addition, the aggregator and grid operator will require evidence that a DER is not "double spending" by selling the same service to two different buyers. Using zero-knowledge proofs that are commonly used in the crypto-asset community,[203] DLT could potentially provide these services, while also protecting the identity and privacy of the aggregator and DER owners, such as information related to the type of DER, capacity, location, ownership, and contract arrangements.

As DERs increase in abundance, they could also enable community-created microgrids where resources are shared peer-to-peer (P2P) within the community. DLT could be helpful in managing the P2P relationships on these microgrids. These microgrids are typically “virtual grids,” in which electricity is traded across the grid operator-owned network. In addition to satisfying customers’ preference to produce and consume within their community, localizing the generation and consumption of electricity could reduce grid congestion, which benefits users inside and outside of the community. P2P energy trading requires some of the same enabling technologies as crypto-assets, namely cryptography-based user authentication, a market-making mechanism and payment system via smart contracts, a tamper-resistant ledger of transactions, and complete auditability. P2P energy trading on networks could use low-energy consumption consensus mechanisms, such as PoS.

There is potential for blockchain and DLT to facilitate the development of environmental and energy markets, including carbon markets,[204,205] distributed energy resource coordination, and general supply chain management. Blockchain and DLT are enabling technologies that are being explored in various markets. However, other solutions might work as well or better. The U.S. government should seek to facilitate innovation that addresses market challenges, aligns with environmental and equity objectives, and appropriately ensures customer and investor protection and market integrity.

5. Appendices

Table A.1

Summary of the most recent published electricity usage estimates of selected PoW and PoS blockchains (2021-2022)[206]

Crypto-Asset	Market Valuation in August 2022 ($billion)	Consensus Mechanism	Date of Estimate(s)	Global Electricity Usage (TWh/y)			Source
				Best Estimate	Lower Value	Upper Value	
Bitcoin	$389	PoW	8/15/2022	88.6	38.2	179.3	https://ccaf.io/cbeci/index
			8/15/2022	144.9	62.6		https://digiconomist.net/bitcoin-energy-consumption
Ethereum	$185	PoW	8/15/2022	93.9	15.6		https://digiconomist.net/ethereum-energy-consumption
			8/15/2022	22.9	16.5	32.2	https://kylemcdonald.github.io/ethereum-emissions/
Cardano	$15	PoS	9/6/2021		1.4E-04	4.4E-03	https://arxiv.org/abs/2109.03667
			8/8/2021	6.0E-04			https://www.carbon-ratings.com/dl/pos-report-2022
Solana	$11	PoS	10/9/2021	2.0E-03			https://www.carbon-ratings.com/dl/pos-report-2022
Dogecoin	$8	PoW	8/15/2022	3.8			https://digiconomist.net/dogecoin-energy-consumption
Polkadot	$8	PoS	7/5/2021		1.4E-05	4.4E-04	https://arxiv.org/abs/2109.03667
			8/29/2021	7.0E-05			https://www.carbon-ratings.com/dl/pos-report-2022
Avalanche	$6	PoS	10/23/2021	4.9E-04			https://www.carbon-ratings.com/dl/pos-report-2022
Algorand	$2	PoS	8/12/2021		5.4E-05	1.7E-03	https://arxiv.org/abs/2109.03667
			8/17/2021	5.1E-04			https://www.carbon-ratings.com/dl/pos-report-2022
Tezos	$1	PoS	8/12/2021		1.9E-05	5.9E-04	https://arxiv.org/abs/2109.03667
			8/25/2021	1.1E-04			https://www.carbon-ratings.com/dl/pos-report-2022

Table A.2

Current performance characteristics of selected permissionless blockchain consensus algorithms[207]

	Proof of Work (PoS)	Proof of Stake (PoS)	Proof of Capacity (PoC)	Practical Byzantine Fault Tolerance (PBFT)
How it works	Miners compete using computational power to solve a complex cryptographic problem	Validating nodes offer crypto-assets as a stake to establish trust instead of computational power	Miners compete using available storage disk space instead of computational power	Majority of voting nodes defines consensus
Examples	Bitcoin, Ethereum, Dogecoin	Ethereum 2.0, Cardano, Solana, Algorand, Tezos	Signa (formerly Burstcoin)	Zilliqa
Electricity consumption	High (0.4% to 0.9% of global electricity usage in August 2022)	Low (less than 0.001% of global electricity usage in 2021)	Expected to be low due to the energy efficiency of storage drives, but current adoption scale is low	Could be higher than PoS due to potentially high node counts, but lower than PoW
Scalability	High	High	High	Low to medium
Throughput	Low	Medium to high	Medium	Medium to high
Latency	Medium to high	Low to medium	Medium	Medium to high
Security	High	High	Subject to further testing	High
Decentralization	High	High	High	Medium to high

Table A.3

Computing device numbers and power requirements for select crypto-assets in 2021

Network	Consensus Mechanism	Date	Computing Devices in 2021		Power Use (Watt/device)[208]
			Number	Type	
Ethereum 2.0	PoS	5/7/21	183,753	Validator Nodes	6 – 168
Algorand	PoS	8/12/21	1,126		
Cardano	PoS	9/6/21	2,958		
Polkadot	PoS	7/5/21	297		
Tezos	PoS	8/12/21	399		
Bitcoin	PoW	5/14/21	2,900,000	Mining Rigs	1,975 – 3,472

Table A.4

Compilation of published GHG emission estimates for crypto-asset mining using the PoW consensus mechanism. For appropriate precision, results rounded to two significant figures

		Emissions			Emissions factor		
		Average	Minimum	Maximum	Average		
Blockchain	**Time Period**	**Mt CO_2 eq./y**	**Mt CO_2 eq./y**	**Mt CO_2 eq./y**	**g CO_2/ kWh**	**Emissions Factor Spatial Unit**	**Source**
Ethereum, Litecoin, Monero	1/2016-6/2018	0.4	0.1	0.6		country	Krause and Tolaymat 2018
Bitcoin	1/2016-6/2018	3.2	1.2	5.2		country	Krause and Tolaymat 2018
Bitcoin	2017	2.8	2	3.6		country, province (China), state (USA)	Calvo-Pardo et al. 2022
Bitcoin	2017	16	2.9	35		country	Houy 2019
Bitcoin	2017	16				country	Masanet et al. 2019
Bitcoin	2017	69				country	Mora et al. 2018
Bitcoin	2018	16	14	18		country, province (China), state (USA)	Calvo-Pardo et al. 2022
Bitcoin	2018	17				country, province (Canada, China), state (USA)	Kohler and Pizzol 2019
Bitcoin	2018	22	22	23		country	Stoll et al. 2019
Bitcoin	2018	24	19	30	480	country, province (China), state (USA)	de Vries 2019
Bitcoin	2019	15	13	17		country, province (China), state (USA)	Calvo-Pardo et al. 2022
Bitcoin	2021	65			570	country, province (China), state (USA)	de Vries et al. 2022
Dogecoin	2022	2.2					Digiconomist 2022-05-30
Ethereum	2022	49					Digiconomist 2022-05-30
Bitcoin	2022	110				country, province (China), state (USA)	Digiconomist 2022-05-30
Bitcoin, Dogecoin,	2022	160				country, province (China), state (USA)	Digiconomist 2022-05-30

		Emissions			Emissions factor		
		Average	Minimum	Maximum	Average		
Blockchain	**Time Period**	**Mt CO_2 eq./y**	**Mt CO_2 eq./y**	**Mt CO_2 eq./y**	**g CO_2/ kWh**	**Emissions Factor Spatial Unit**	**Source**
Ethereum							
Dogecoin	2022	2.2					Digiconomist 2022-06-08
Ethereum	2022	47					Digiconomist 2022-06-08
Bitcoin	2022	110				country, province (China), state (USA)	Digiconomist 2022-06-08
Bitcoin, Dogecoin, Ethereum	2022	160				country, province (China), state (USA)	Digiconomist 2022-06-08
Dogecoin	2022	1.5					Digiconomist 2022-06-16
Ethereum	2022	30					Digiconomist 2022-06-16
Bitcoin	2022	81				country, province (China), state (USA)	Digiconomist 2022-06-16
Bitcoin, Dogecoin, Ethereum	2022	110				country, province (China), state (USA)	Digiconomist 2022-06-16

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List of Acronyms

Abbreviation	**Definition**
ASIC	Application-Specific Integrated Circuit
CO_2	Carbon Dioxide
DER	Distributed Energy Resources
DOE	Department of Energy
DLT	Distributed Ledger Technologies
eGRID	Emissions & Generation Resource Integrated Database
EH/S	Exahash per Second
EPA	Environmental Protection Agency
ERCOT	Electricity Reliability Council of Texas
g CO_2 eq./y	Grams of Carbon Dioxide-Equivalent per Year
GHG	Greenhouse Gas
g/kWh	Grams per Kilowatt-Hour
GW	Gigawatts
IPCC	Intergovernmental Panel on Climate Change
IRA	Inflation Reduction Act
J/GH	Joules per Gigahertz
kWh	Kilowatt-Hour
Mt CO_2/y	Million Metric Tons of Carbon Dioxide Per Year
MWh	Megawatt-Hour
OSTP	Office of Science and Technology Policy
P2P	Peer-to-Peer
PoS	Proof of Stake
PoW	Proof of Work
TH/S	TeraHash per Second
TWH/y	TeraWatt-Hours per Year
VCM	Voluntary Carbon Markets

Interagency Policy Committee

- Commodity Futures Trading Commission (CFTC)
- Consumer Financial Protection Bureau (CFPB)
- Department of Commerce (DOC)
- Department of Defense (DOD)
- Department of Energy (DOE)
- Department of Homeland Security (DHS)
- Department of Justice (DOJ)
- Department of Labor (DOL)
- Department of State (DOS)
- Department of Transportation (DOT)
- Department of Treasury (Treasury)
- Environmental Protection Agency (EPA)
- Executive Office of the President (EOP)
- Federal Deposit Insurance Corporation (FDIC)
- Federal Reserve Board (FRB)
- General Services Administration (GSA)
- National Science Foundation (NSF)
- Office of the Director of National Intelligence (ODNI)
- Securities and Exchange Commission (SEC)
- U.S. Agency for International Development (USAID)

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[196] Additional context: A cap-and-trade program establishes a maximum limit or “cap” on overall emissions from a group of identified sources, such as power plants. The cap is calibrated to reduce emissions to achieve a desired environmental effect. Based on the cap, a designated authority, typically established by a statute and/or regulation, issues “allowances” that permit regulated sources to emit a set amount of a pollutant for each allowance (frequently one ton). Sources subjected to the cap are required to monitor and report emissions, and surrender to a designated authority one allowance for every unit of pollution that they emitted during the relevant compliance period. These allowances are typically tradeable instruments, thus the name “cap and trade.” An example of this is EPA’s Acid Rain Program established under Title VI of the Clean Air Act. *See,* Acid Rain Program at https://www.epa.gov/acidrain/acid-rain-program.

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[206] "Best estimate" refers to authors' expected, central, or "best guess" published value when available; market valuation data are as of 26-Aug-22, based on https://coinmarketcap.com/; upper and lower values refer to ranges or bounds published by authors

[207] Adapted from Lei et al. (2021) https://doi.org/10.1016/j.enpol.2021.112422 and Ferdous et al. (2020). Blockchain consensus algorithms: A survey. https://arxiv.org/abs/2001.07091; decentralization refers to decentralization potential in theory; in practice, decentralization can be reduced through concentration of mining rigs or validators into a limited number of operators

[208] For PoS networks, the validator node numbers and power use range are estimated by Platt et al. (2021); for Bitcoin, the mining rig number is estimated by DeVries and Stoll (2021) and the power use range is based on the range of power use by rigs estimated to be economically viable by DeVries and Stoll (2021) on 5/14/21.