Leveraging Bitcoin miners as flexible load resources for power system stability and efficiency

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Abstract

This review examines the role of Bitcoin mining as a possible catalyst for accelerating the global shift towards clean energy and effective power grid management. Amidst the evolving landscape of energy systems and grid operations, demand response and flexible load resources are becoming crucially important. We focus on the emergence of Bitcoin mining as an important feature for industrial-scale demand response, making use of miners' inherent characteristics of interruptibility and swift response to enhance grid flexibility. Bitcoin mining can also directly utilize stranded energy resources, suggesting it is a novel technology for improving grid efficiency and facilitating rapid growth in renewable energy production. By leveraging their unique attributes, Bitcoin miners demonstrate how they might contribute to the coming energy transition, highlighting the potency of cross-cutting financial and technological innovation in shaping a sustainable and interconnected energy framework.

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Introduction

As Bitcoin mining rapidly became a significant industrial energy consumer, considerable attention was directed towards quantifying its energy usage (de Vries, 2018; Mora et al., 2018; Stoll et al., 2019) and environmental impact (Goodkind et al., 2020). The initial research that assessed Bitcoin's energy consumption helped solidify the widespread perception of Bitcoin as an energy-intensive technology without inherent value (Sovacool et al., 2022). Despite some high-profile research being subject to criticisms (Carter, 2021; Dittmar and Praktiknjo, 2019; Houy, 2019; Masanet et al., 2019), the narrative of Bitcoin's energy wastefulness has been reflected in policy initiatives aimed at regulating the mining sector (OSTP, 2022; Riley, 2021).

A lack of awareness about what Bitcoin is and how it works among many members of the public and government agencies complicates efforts to effectively communicate the purpose and rationale for Bitcoin's energy intensity. Bitcoin operates dynamically, adapting the complexity of cryptographic challenges based on network hash power, which itself is a function of power costs, the efficiency of specialty processing chips, and Bitcoin market price. This dynamic nature introduces complexities associated with data collection, model extrapolation, technological advancement, and the incorporation of uncertainty (Lei et al., 2021). Ongoing research into the net effects of integrating Bitcoin into both existing and new energy supply and transmission systems has recently commenced, revealing potentially positive influences of Bitcoin on the energy sector (Hallinan et al., 2023; Ibañez and Freier, 2023; Liu et al., 2023; Menati et al., 2023; Niaz et al., 2022a; Niaz et al., 2022b). The presumption that all electricity consumed by the Bitcoin network contributes directly to an expansion in global energy consumption and climate change oversimplifies the situation, and ignores other potentially counterintuitive outcomes (Rudd, 2023b).

In this review, we emphasize Bitcoin mining's potential to help contribute to the sustainable global energy transformation. We briefly touch on Bitcoin's potential contributions to methane emission reduction and renewable energy infrastructure but our principal focus is on Bitcoin's role as a resource for enhancing power system flexibility and stability, and in efficiently managing energy production and electricity grids. Our examination of Bitcoin mining's role is rooted in the specific context of the Electricity Reliability Council of Texas (ERCOT) grid. This exploration underscores the interplay between technological innovation and energy systems, providing insights that might transcend local contexts and contribute to the broader discourse on orchestrating the energy transformation.

Understanding Bitcoin's energy consumption

Bitcoin's Proof-of-Work consensus mechanism

Satoshi Nakamoto's conceptualization of Bitcoin (Nakamodo, 2008) drew upon numerous earlier ideas from computer science and cryptography research (Narayanan and Clark, 2017), and resulted in the creation of a decentralized, economical, and 'trustless' public digital ledger for global peer-to-peer financial and informational transactions. Bitcoin's Proof-of-Work (PoW) consensus mechanism rewards the Bitcoin producer, the 'miner', who successfully solves a cryptographic challenge based on the SHA-256 algorithm. This achievement grants the successful miner the authority to generate the subsequent block, collecting block creation fees and transaction fees. Each newly minted block contributes to the continuous chain of connected blocks systematically timestamped within the ledger at approximately 10-minute intervals. Any attempt to falsify information within the Bitcoin ledger necessitates not only altering the target transaction but also all previous linked transactions.

The significance of the PoW consensus mechanism lies in its assurance of the global ledger's immutability, effectively embedding energy in digital format to guarantee the security and permanence of transaction records.

Bitcoin miners utilize sophisticated computers equipped with energy-intensive application-specific integrated circuit (ASIC) chips, employing brute force to solve SHA-256 hashes. By 2023, the intensely competitive Bitcoin mining sector achieved a hash rate of >400 exahash per second (data.hashrateindex.com/network-data/btc), corresponding to about 0.2% of global energy production and 0.6% of global electricity consumption (ccaf.io/cbnsi/cbeci/comparisons). The inherent transparency of the Bitcoin protocol facilitates the evaluation of its energy consumption. Some important variables are, however, difficult to ascertain and contextual challenges arise from assumptions about mining operations and the potential role of Bitcoin in carbon dioxide equivalent (CO2e) mitigation strategies.

Early modeling of Bitcoin energy use and environmental impacts

Research on Bitcoin's energy consumption includes regional and global modeling, as well as case-specific investigations. Dwyer and Malone (O'Dwyer and Malone, 2014) were the first to attempt quantifying miners' energy consumption in the Bitcoin network. Vranken (2017) synthesized initial findings on Bitcoin network energy usage, while Krause and Tolaymat (2018) estimated and compared Bitcoin's energy consumption with that of traditional precious metals mining industries.

In a speculative vein, de Vries delved into both a theoretical discussion (2018) and a model-based analysis (2020) of network energy utilization. Mora et al. (2018) suggested Bitcoin's energy consumption could lead to a global temperature rise exceeding 2°C. The Mora paper, arising from a graduate-level course assignment at the University of Hawai'i at Mānoa, has exerted substantial influence on the global discourse surrounding Bitcoin's energy consumption. This influence persists despite considerable critique directed towards its methodological inadequacies and implausible projections (Dittmar and Praktiknjo, 2019; Houy, 2019; Masanet et al., 2019). Koomey (2019) synthesized research up to 2019, informing best practices for quantifying Bitcoin's energy consumption (Lei et al., 2021).

Case-specific studies have been used to assess Bitcoin mining's impact on local energy costs in New York (Benetton et al., 2021) and to explore localized 'Bitcoin boomtown' effects as miners capitalized on affordable hydroelectric energy in Chelan County, Washington (Greenberg and Bugden, 2019). Roeck and Drennen (2022) analyzed emissions from a Bitcoin mining operation adjacent to a natural gas plant in upstate New York.

Modeling Bitcoin's direct energy use – common challenges

Data availability

Estimating Bitcoin's energy consumption has been facilitated in recent years by dynamic indices such as the Cambridge Bitcoin Energy Consumption Index (CBECI) and quarterly disclosures from industry groups like the Bitcoin Mining Council. While energy consumption estimates may vary due to assumptions about active hardware distribution on the network, influencing consumption assessments, these estimates generally exhibit relative stability (ccaf.io/cbnsi/cbeci). Reports exploring projections of Bitcoin's energy growth are also available (Carter, 2021; CoinShares, 2022). An increasing amount of data from private mining companies are also available and have been used recently (Menati et al., 2023; Niaz et al., 2022a).

Hardware mix

The hardware composition used in Bitcoin mining has evolved over time. Originally dominated by graphics processing units (GPUs), mining gradually shifted toward ASICs due to their enhanced efficiency. This transition significantly influenced energy consumption and the overall hardware mix adopted by miners (bitcoinminingcouncil.com/wp-content/uploads/2023/08/BMC-H1-2023-Presentation.pdf). However, to comprehensively understand Bitcoin's energy footprint, additional insights about the historical and current hardware mix and its implications for energy consumption must be considered. A new nonce-based ‘fingerprinting’ approach to estimate ASIC energy use and aggregate Bitcoin energy consumption was introduced in May 2023 by Coin Metrics (Helmy et al., 2023), who estimated that aggregate network energy consumption was about 16.5% lower than CBECI estimates. Very recently (August 2023), CBECI also made a downward revision in their Bitcoin energy use estimates to reflect their increased understanding of the role of advancing mining technology on energy consumption (www.jbs.cam.ac.uk/2023/bitcoin-electricity-consumption/).

Mining pools

Assessing emissions associated with the electricity powering Bitcoin miners has often relied on anecdotal or IP-geolocation-based data. This approach introduces speculation due to the limited disclosure practices of certain miners and the dynamic nature of mining operations. An erroneous assumption sometimes arises that mining pools' locations directly align with individual miners' locations, impacting emissions accuracy. Additionally, assuming that miners adhere to a uniform global or country-level energy mix misrepresents the diverse energy sourcing strategies miners employ. For example, Stoll et al. (2019) took a step towards a more comprehensive approach when focusing on the four Chinese provinces of Yunnan, Sichuan, Inner Mongolia, and Xinjiang. They integrated pool IP geolocation, miner device IoT localization, and IP addresses from nodes to derive regional carbon intensities. Despite those advancements in disaggregation, data accuracy remains challenging due to the imprecision of pool IP address geolocation, miners’ efforts to hide their location by using VPNs, and miners' attempts to conceal their locations for various reasons (e.g., keeping information about cheap power sources concealed).

Carbon intensity assumptions

When considering the nuances of assessing Bitcoin's emissions, it is crucial to acknowledge the diversification in miners' energy procurement practices, often diverging from generic country-level energy compositions. Their distinct behaviors render the assumption of consistent energy sources impractical.

Miners strategically harness stranded or underutilized energy sources, a notable instance being stranded hydro in China's Sichuan and Yunnan provinces (Köhler and Pizzol, 2019; Ma, 2021). Stranded hydro provides an almost emissionless energy supply for Bitcoin mining, a feature that is lost if China's aggregated carbon intensity is directly assigned to miners. Assuming that all energy was generated by coal if it was, in fact, generated by hydro would overestimate CO2e by almost 50 times (ccaf.io/cbnsi/cbeci/ghg).

Despite acknowledging the absence of data concerning miners' operational locations, Krause and Tolaymat (2018) projected Bitcoin's emissions by applying the carbon intensities of seven country grids (Canada, Korea, Japan, USA, China, Australia, India) to miners. However, that approach does not reflect the reality that miners do not align with the energy mix of any specific large country. It is imperative for scholars to scrutinize studies attributing generic energy mixes to miners, as those disregard the intricate sourcing strategies miners employ.

The CBECI mining map (ccaf.io/cbeci/mining_map/methodology) refined location-based data somewhat by incorporating mining pool data, accounting for a substantial portion of Bitcoin's hashrate. Due to regulatory sensitivities in some regions, CBECI data was, however, mainly presented at the country level. In August 2021, the US-based mining pool Foundry released state-level data within the United States, shedding light on the geographic distribution of mining activities in the country. Subsequently, de Vries et al. (2022) used data from Foundry and CBECI to generate an updated estimate of Bitcoin mining's CO2e emissions. However, their reliance on August 2021 data attributed 18 percent of the network's activity to coal-heavy Kazakhstan poses concerns, given Kazakhstan's subsequent reduction in domestic mining activities over the ensuing eight months. More pragmatic projections of Bitcoin's future energy trajectory can be found in the work of Dai et al. (2023).

Modeling Bitcoin's net energy impact – confounding factors

Methane use and CO2e mitigation

Innovative Bitcoin miners have strategically positioned themselves to harness unconventional energy sources, highlighting the adaptability inherent in the mining process. Given the modest infrastructure demands of Bitcoin mining, predominantly relying on electricity and specialized ASIC hardware, miners possess the latitude to explore energy sources beyond traditional grids and internet infrastructure. This strategic positioning becomes feasible in the presence of accessible and low-cost energy sources, and Starlink internet connections.

Among these unconventional sources, flared methane, a byproduct of oil extraction processes and potent greenhouse gas (Cicerone and Oremland, 1988; Wuebbles and Hayhoe, 2002), emerges as an important use case because of the high international priority given to mitigating methane emissions (IGSD, 2023; Malley et al., 2023; Nisbet et al., 2020; World Bank, 2022). In situations where pipelines are absent or transportation proves uneconomical, surplus natural gas is frequently vented or flared at well-pads, contributing to substantial CO2e emissions (Brandt et al., 2014). In 2021 alone, 140 billion cubic meters of gas were flared or vented (World Bank, 2022), contributing >300-m tonnes of CO2e to the atmosphere.

A pioneering approach within the Bitcoin mining community involves the utilization of electricity generated from waste methane. Miners are increasingly installing generators at oil fields, turning a one-time waste asset into a valuable resource (Malfuzi et al., 2020; Snytnikov and Potemkin, 2022).

De Vries et al. (2022) posit that powering a generator with natural gas that would otherwise be flared yields no emissions reduction, grounding their assertion in the assumption that flare combustion efficiency stands at 98%, as mandated by the EPA. However, practical assessments of flaring efficiency reveal significantly lower combustion efficiency rates. Combustion efficiencies of only 68% were observed among miners in Alberta, with efficiency diminishing alongside wind speed (2001). Drawing on aerial surveys, Kleinberg (2019) estimated that GHG emissions resulting from flaring in the Bakken region surpass by 79% the levels that would occur at a combustion efficiency threshold of 98%. Consequently, orchestrating a controlled reaction in a natural gas generator represents a substantial enhancement over the default flaring model in terms of emissions reduction. The net effect of flaring on the economics of marginally profitable fossil fuel production assets is an area requiring more research (Rudd, 2023a).

Research conducted by Coinshares (2022) supports the idea that Bitcoin mining can play a significant role in reducing emissions associated with flare gas. Flaring methane in oilfields is known for its inefficiencies, and focusing on mitigating 250 MW of flare gas through Bitcoin mining could potentially lead to an annual reduction of 2.1 million metric tons of CO2e emissions worldwide. This reduction represents approximately 5.2% of Bitcoin's estimated 41 million metric tons of CO2e emissions in 2021 (the USA contributing 47% of these global emissions that year).

To provide context, the current USA methane emissions reduction plan (The White House, 2022) aims to achieve a 75% reduction in methane emissions from the oil and gas sector by 2035, equivalent to a cumulative reduction of 41 million metric tons of methane over 13 years, which is roughly 920 million metric tons of CO2e. Therefore, flare gas mitigation efforts by Bitcoin mining could account for approximately 3.0% of the annual emissions reduction target in the USA's oil and gas sector. While 3% may seem modest, it's important to emphasize that mitigating anthropogenic methane emissions from various sources is crucial (IGSD, 2023). Expanding Bitcoin mining's methane mitigation efforts beyond the USA to regions identified as methane emission hotspots within (Lauvaux et al., 2022) and beyond (Maasakkers et al., 2022) the oil and gas sector could significantly enhance the contribution of Bitcoin miners to these mitigation endeavors.

Even when commercially-viable Bitcoin mining is not a tenable prospect, there exists the potential to use miners to monetize waste gas and channel resources into mitigating the expenses associated with the closure of abandoned wells and other methane sources, such as landfills and agricultural operations. Monetizing methane emissions also holds the promise of further diminishing the carbon footprint tied to hydrocarbon extraction by financing part of the costs of developing new carbon capture technologies (Niaz et al., 2022b; Snytnikov and Potemkin, 2022).

Bitcoin mining and renewable energy synergy

An emerging body of literature is shedding light on the symbiotic relationship between Bitcoin mining and renewable energy sources. The integration of these two seemingly disparate domains offers an opportunity for renewable energy asset owners to optimize their resources and economics in novel ways. By introducing a distinct buyer, an anchor tenant, of energy into the traditional grid framework, renewable energy facilities can diversify their consumer base, thereby potentially enhancing the profitability of underutilized energy resources. No matter what the time of day, the weather conditions, or market-wide demand for electricity, Bitcoin miners will always be able to utilize electricity generated by renewable energy producers that would otherwise have been wasted.

Bastian-Pinto et al. (2021) underscored this synergy by showcasing how wind farms can effectively hedge against electricity price fluctuations through strategic investments in Bitcoin mining. By integrating traditional grid buyers and Bitcoin mining operations, wind farm developers can craft diversified portfolios that enhance the flexibility and monetization of their energy assets. This approach not only enhances financial resilience but also contributes to the overall stability of the renewable energy sector.

The Bitcoin Clean Energy Initiative by Square (now known as Block) adds to this perspective with a whitepaper and model outlining how Bitcoin miners could enhance the economics of new wind and solar installations, particularly when combined with energy storage solutions like battery technology (squareup.com/ca/en/press/bcei-white-paper). This integrated approach could address issues related to capacity factors and enhance the overall efficiency of renewable energy utilization.

The concept of location-agnostic Bitcoin mining also emerges as a significant consideration. Shan and Sun (2019) explored the feasibility of co-locating Bitcoin mining operations with wind and solar generation facilities to improve monetization and reduce energy curtailment. Their investigation, based on data from the California Independent System Operator (CAISO), suggests that Bitcoin mining's independent energy demand can help mitigate renewable energy curtailment, offering an alternative avenue for monetization. Malfuzi et al. (2020) examined the viability of using renewable biogas setups for Bitcoin miner power generation, further highlighting the potential of coupling Bitcoin mining with sustainable energy sources.

Power system flexibility and demand-side management

Need for demand response in the energy transition

The International Renewable Energy Agency (IRENA) emphasized the value of large, controllable industrial loads in effectively managing demand (2018). However, despite its potential, DR remains significantly underdeveloped, accounting for a mere 0.5% of global generation, or around 40 GW deployed (IEA, 2018a). To meet the 2050 Net Zero Scenario, the International Energy Agency (IEA) projected that DR capabilities must expand to encompass 500 GW globally by 2030 (IEA, 2021). While hydro power and nuclear energy offer low-carbon intensity and can function as baseload generation, nuclear energy's lack of flexibility and hydro power's limitations due to geography and seasonality are apparent.

The integration of variable renewable energy (VRE) into modern grids poses complex challenges tied to their intermittency and unpredictability (Denholm et al., 2021; Impram et al., 2020; IRENA, 2018; Kaushik et al., 2022). Renewable energy sources are progressively claiming larger shares of contemporary grids. The transition from conventional fossil-fuel-based generation, such as natural gas and coal, to a greater reliance on wind and solar power amplifies fluctuations both intraday and seasonally within grid energy generation profiles. This shift requires innovative solutions for grid stability and efficient energy management.

Grid interconnections, dispatchable thermal generation, and hydro storage presently fulfill pivotal roles in mitigating the impacts of renewable energy intermittency. Grid interconnections enable the exchange of energy among neighboring grids with diverse generation patterns, while dispatchable thermal plants and hydro storage provide the adaptability to adjust energy generation in response to demand fluctuations. Kaushik et al. (2022) anticipated that future power systems will adopt larger-scale battery storage, already a reality in the ERCOT grid for many years, and embrace demand response (DR) from load centers to further augment power system flexibility. DR involves modifying electricity consumption patterns to coincide with periods of elevated market prices or grid reliability concerns (FERC, 2010).

Sources of power system flexibility

Power system flexibility draws from four primary sources: conventional generation, storage, transmission, and demand-side management. In the current landscape, dispatchable conventional generation stands as the dominant contributor to flexibility, with thermal and hydro plants accounting for a substantial 85% of the total flexibility available.

Conventional approaches for power system flexibility

Storage encompasses a range of physical processes such as pumped hydro, flywheel energy storage, compressed air, and various battery technologies like lithium-ion, lead-acid, nickel-cadmium, and zinc-bromide (Kaushik et al., 2022). Non-run-of-river hydro power in 2018 constituted the largest source of flexibility, accounting for approximately 32% of the global total (IEA, 2018a). Pumped hydro accounted for 4% of total power system flexibility, further contributing to the energy mix, while conventional non-hydro storage adds an additional half a percentage point of flexibility.

Load flexibility depends on DR capabilities provided by industrial, commercial, and residential sectors. It's important to note that wholesale DR is mainly accessible to industrial loads. DR involves specific demand-side management programs that optimize electricity consumption patterns to align with supply dynamics (IRENA, 2018). These programs can be market-driven, leveraging price signals for sophisticated customers in deregulated markets, or contractually structured. Retail time-of-use DR initiatives incentivize customers to shift consumption to low-demand periods.

Flexible generation, a historical mainstay for achieving power system flexibility, comes at a notable CO2e cost. Thermal sources capable of dispatchable generation to meet varying loads include open-cycle gas turbines, natural gas, and oil-fired internal combustion engines, prized for their considerable flexibility. The array of flexible generation sources also encompasses combined-cycle gas turbine plants, biogas plants, and other alternatives.

Different thermal plants exhibit diverse capabilities (IRENA, 2019). Flexibilized hard coal plants cannot be ramped quickly; for example, a 100 MW plant might need to run a minimum of 20 MW and cannot be cycled quickly to come back after being taken offline. They may have a maximum ramp rate of ~4% of nominal power per minute and a minimum uptime and downtime of 48-hours. In contrast, conventional hard coal power plants offer minimal flexibility but provide steady and uninterrupted base load.

Open-cycle gas turbines, on the other hand, boast rapid 5- to 10-minute startup times, low associated costs, a ramp rate reaching 15% of nominal power per minute, and minimal uptime and downtime of 30-minutes to 1-hour. Diesel or natural gas-powered internal combustion plants exhibit a 2-minute startup, can ramp to full load within a minute, and feature a minimum uptime and downtime of under five minutes. This renders conventional thermal generation capable of delivering baseload support while remaining adaptable to variable demand through responsive peaker plants, usually powered by natural gas. Meeting renewable energy targets necessitates a transition away from thermal dispatchable generation.

Importance of grid interconnections for flexibility

Electricity networks can also contribute to power system flexibility. The key component here is interconnections, which involve sourcing energy from neighboring grids exhibiting uncorrelated generation patterns. In the United States, for instance, there are three major interconnections: West Interconnection, East Interconnection, and ERCOT. Currently, interconnections account for 5% of global grid flexibility (IEA, 2018a) and are near zero in ERCOT.

The significance of grid interconnections for flexibility becomes increasingly apparent as power grids transition from carbon-intensive baseload and load-following generation derived from hydrocarbons to low-carbon models with higher renewables integration. Throughout history, generation has formed the foundation of grid flexibility, precisely adjusting supply at high frequencies to align with demand fluctuations, sometimes down to a second-by-second scale. While certain conventional generation methods, such as nuclear, lack flexibility almost entirely, coal and combined-cycle gas turbines offer adaptability, serving as either base load or load-following assets.

However, not all sources of power system flexibility are created equal. While conventional dispatchable generation yields high emissions, grid interconnections require robust connectivity and high-voltage transmission infrastructure. Pumped storage's viability depends on geography and access to water sources. Novel energy storage systems, though promising, are currently uneconomical at scale. Kaushik et al. (2022) evaluated these four sources of flexibility, granting ‘flexible load’ top marks due to its flexibility, economic viability, quantity, and maturity. DR, deployable at scale today, stands out for its potential to swiftly stabilize increasingly renewable grids. Barriers to widespread adoption primarily center around market design challenges.

Role of demand-side management in grid flexibility and stability

Introduced in the USA during the 1970s, DR was initially conceived as a minor mechanism for stabilizing the grid. However, over time, loads contributing to DR have transformed into valuable resources in their own right, delivering services comparable to those furnished by dispatchable generation resources. Some 500 GW of DR capacity needs to be integrated into global energy markets by 2030, a substantial increase from the 2020 deployment levels of approximately 50 GW (IEA, 2021).

The role of demand-side management in enhancing grid flexibility and stability is marked by the distinction between retail and wholesale DR programs. In the USA, the availability of demand savings in 2019 amounted to 31 GW from retail DR programs and 31.7 GW from wholesale DR programs, collectively equivalent to 8.3% of summer peak load (FERC, 2021a).

Retail programs

Retail programs involve in-depth metering of residential and commercial electricity usage, leveraging hourly consumption data to settle bills at billing cycle closures. Participation in voluntary retail programs is incentivized through economic rewards. For example, programs can use a time-of-use billing strategy that empowers consumers to optimize energy expenses by aligning their electricity consumption with low-demand periods, thereby benefiting from reduced pricing.

Conversely, during high-demand peak hours, energy consumption is curtailed, often at a premium price. In some instances, advanced notice is communicated to consumers to encourage reduction in usage. This dynamic is supported by the growth of smart metering, connected devices, and emerging load centers like electric vehicle charging stations, which collectively advance retail DR. Smart meter expansion, particularly notable in the USA, paved the way for DR expansion. By 2019, advanced meters had reached a penetration rate of 60% in USA households, a significant increase from 13% a decade earlier (FERC, 2021a). The ability to track consumption hourly serves as a foundation for encouraging load shifting and curtailment during peak periods.

Digitalization is reshaping roles within the energy landscape, introducing demand aggregators, virtual power plants, and energy service companies (Ali et al., 2023; IEA, 2018b). A virtual power plant, for instance, brings together distributed energy resources to engage in energy markets, comprising a collection of residential DR resources (Pudjianto et al., 2007).

Real-time energy pricing is generally shielded from residential consumers due to perceived complexities associated with direct spot power purchasing risks. However, to maximize the effectiveness of DR programs in alleviating grid congestion, real-time, highly localized curtailment signals (often linked to power prices) are crucial.

Wholesale programs

Wholesale DR programs, on the other hand, involve industrial consumers directly competing with supply-side resources and energy storage through auctions managed by Regional Transmission Organizations or Independent Service Operators (RTOs/ISOs). These auctions are geared towards acquiring energy and capacity to meet real-time energy and reliability needs of the power system. Qualification for wholesale DR necessitates industrial consumers meeting RTO's/ISO's technical prerequisites for controllable loads or non-controllable loads.

Controllable loads, an approach pioneered by ERCOT, have the capacity to actively adjust based on real-time basepoint dispatch instructions, offering direct manageability by grid operators in real time. Additionally, more advanced controllable loads can autonomously modify consumption in response to grid frequency changes. This gives rise to the potential for dramatically increasing grid flexibility, an essential grid characteristic needed to integrate rapidly increasing penetration of variable generation into the grid (Denholm et al., 2021; Ela et al., 2016).

Non-controllable loads lack the ability to follow basepoint instructions and include under-frequency relay switches attached to their load centers, allowing grid operators to completely cut off their load. Hence, industrial sources, particularly those with controllable loads, hold substantial potential as supplementary DR providers from a grid perspective.

Nonetheless, not all loads are equipped for DR participation, and considerable variability exists within the eligible load set. Loads vary in aspects such as energy intensity, response time, availability, response cost, consumption granularity, and geographic flexibility (Mellerud, 2021). The optimal load resource would exhibit instantaneous reactivity, responsiveness to localized price signals, continuous curtailment capacity, minimal opportunity cost during downtime, high granularity curtailment, and significant energy contribution in MWh. Established industrial sources of flexible load arise from energy-intensive industrial processes like electrolysis, grinding, heating, or cooling. Interruption of these processes directly impacts business operations and economics. Most industrial processes are intolerant of unscheduled interruption due to potential economic losses, impacts on inbound and outbound logistics, or equipment damage. Among interruptible processes, tolerance for downtime is limited, and full consumption curtailment is often impractical. Physical industrial processes inherently come with technical limitations to load flexibility.

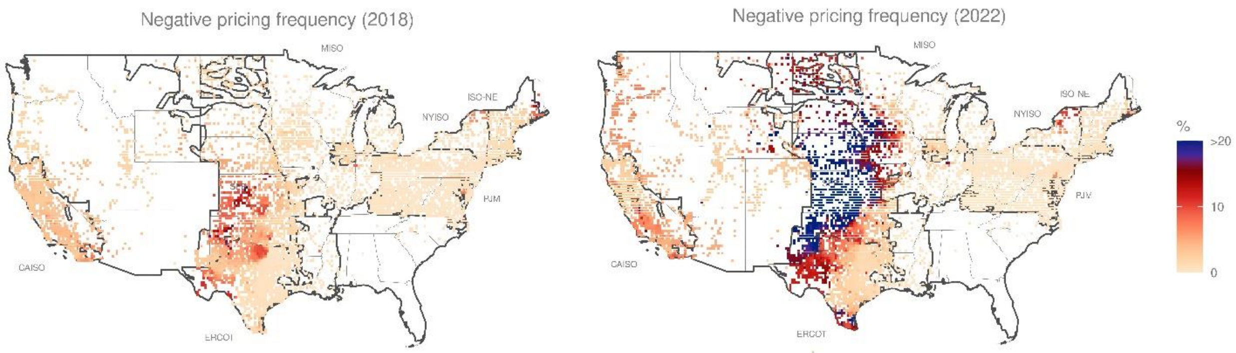
Industries and sources spanning a wide range have been evaluated for their suitability as flexible loads. Historically, industries such as cement, aluminum, and steel production, along with food refrigeration, have demonstrated substantial DR potential. Shoreh et al. (2016) synthesized research on DR participation across high-energy industries including food, steel, aluminum, and paper. Electrolytic processes, particularly in aluminum, chloralkali, potassium hydroxide, magnesium, sodium chlorate, copper, and hydrogen production, were regarded as appropriate for DR due to their substantial power demands and interruptibility capacity.

For instance, aluminum smelting, with its high energy intensity, allows for rapid power control by adjusting the input voltage of the potline or sequentially turning off power to potlines (Siddiquee et al., 2021). Cement plants offer DR by curtailing quarrying and milling processes, enabling peak load reductions of up to 70% for three hours. Steel plants exhibit the potential for peak load reductions of up to 96% of peak load reduction for approximately two hours by pausing electrical demand associated with arc and ladle furnaces (arcuspower.com/pwrstream-services/). Timber mills contribute to DR by achieving up to 80% peak load reduction for three hours through interruptions in kilns, planers, and sawmills. However, the sequential nature of processes in these plants introduces complexities, rendering immediate interruption impractical and indefinite curtailment unachievable. Irrespective of approach, industrial DR can be unreliable because of their inability to ramp up and down in a controlled manner. For example, an arc furnace can either be on, or off. This immediate drop in power consumption is the exact inverse to a power plant tripping offline, increasing the grid frequency all in one shot.

The challenge of integrating variable renewable energy

Solar and wind sources exhibit intraday and seasonal variations, leading to their classification as variable generation. Integrating VRE sources like wind and solar presents intricate challenges due to their intermittency and location-based constraints (IEA, 2023; Veers et al., 2019). Moreover, economic curtailment of VRE resources becomes significant as they contribute more to the power mix (Bird et al., 2016; Frew et al., 2021). This issue becomes evident with new wind and solar installations in the USA, coupled with insufficient transmission infrastructure, resulting in frequent episodes of negative wholesale pricing (Seel et al., 2021). Over the past decade, such instances of negative pricing surged considerably, accounting for 6.3% of all hours in 2022 across USA wholesale market nodes (Figure 1). As more wind and solar get added to locations like Texas, with its excellent wind speeds and sun quality, and with limited or at-capacity transmission, the frequency of negative priced power may increase further in the near future (Frew et al., 2019; Frew et al., 2021).

Among the low-carbon generation sources, solar and wind (including photovoltaic and thermal) are being aggressively integrated into global power grids. Forecasts by Kaushik et al. (2022) predicted a 60% variable generation penetration in China and an 80% penetration in the USA by 2050. Some regions have already achieved high penetration: Denmark, for example, derives 50% of its power from wind and solar (denmark.dk/innovation-and-design/clean-energy). Wind capacity worldwide surged by an average of 14% from 2010 to 2020, reaching 743 GW, accounting for 6% of the global power mix (Lee et al., 2021). Ren et al. (2017) anticipated wind would account for 18.8% of global production by 2030, while the Global Wind Energy Council envisions wind reaching 30% of the global total by 2050 (Lee et al., 2021). In 2021, wind and solar collectively comprised 90% of planned new electric generating capacity in the USA and 75% globally (www.seia.org/solar-industry-research-data).


Negative pricing frequency (2018)

Negative pricing frequency (2022)

Figure 1. Negative electricity pricing in the USA in 2018 (top panel) and 2022 (bottom panel) (chart generated from data at https://emp.lbl.gov/renewables-and-wholesale-electricity-prices-rewep)

Given the challenging forecasting and fluctuating nature of VREs, RTOs/ISOs with substantial VRE penetration are actively pursuing reforms to enhance operational flexibility. CAISO, MISO, ERCOT, and SPP have introduced new ancillary service products designed to provide short-term ramping capabilities to address shifting system requirements arising from increased VREs (FERC, 2021b). They underline the industry consensus that RTOs/ISOs will require heightened operational flexibility from resources to ensure reliable service as the resource mix evolves with the inclusion of more VREs and weather-dependent distributed energy resources.

Recognizing that the importance of power system flexibility scales with VRE integration, the IEA has outlined VRE integration phases in a 2018 framework (IEA, 2018a). Phase 1 encompasses grids with negligible VRE shares where flexibility is unnecessary to counteract renewables' intermittency. Phase 2 arises when VRE constitutes around 5-10% of the mix, and existing resources are sufficient to manage the impact of VRE on the grid. In Phase 3, as VRE grows to approximately 10-30%, a systematic increase in power system flexibility is required to accommodate the influx. Phase 4 occurs when VRE constitutes a significant majority of power during peak generation periods, necessitating substantial regulatory and operational grid adjustments. Phase 5, as yet unrealized at the time of writing, involves VRE entirely powering the grid during specific periods, marked by substantial surpluses and routine supply curtailment. This phase requires demand shift synchronization with supply, new demand creation through electrification, and enhanced flexibility via interconnections.

As of 2016, Denmark, South Australia, and Ireland were the only geographies in Phase 4, according to the IEA's framework. Advancing to the latter VRE integration phases demands technologies and reforms that remain speculative, such as the 'electrification of other end-use sectors, seasonal storage, and the use of synthetic fuels like hydrogen' (www.iea.org/articles/will-system-integration-of-renewables-be-a-major-challenge-by-2023). The IEA emphasized that demand-side flexibility will play a critical role, complementing the supply-side, which has traditionally dominated, owing to general electrification trends and the emergence of new load types. In fact, the IEA considers flexible demand to be at least as important as flexible supply (www.iea.org/articles/energy-transitions-require-innovation-in-power-system-planning).

Bitcoin miners as flexible load resources

Bitcoin's technical capacity for demand response

Bitcoin miners emerge as a uniquely adaptable category of loads, demonstrating remarkable flexibility and the ability to curtail their energy consumption in a controlled manner with minimal latency over extended periods. Fridgen et al. (2021) highlighted the potential of Bitcoin mining to provide energy flexibility that stabilizes renewable grids and encourages the deployment of renewable resources. Rhodes et al. (2021) emphasized the role that flexible loads, including those from Bitcoin mining, could play in the decarbonization of ERCOT by accommodating higher levels of renewables. They argued that the grid's ability to manage intermittent supply depends on robust flexibility on the demand side, suggesting that the strategic incorporation of flexible loads could drive the decarbonization of grids transitioning to renewables.

The emergence of Bitcoin miners as a distinctive type of flexible load resource introduces a potentially transformative dimension to grid flexibility. Traditional DR, often associated with physical industrial processes, typically exhibits response times measured in minutes to hours, necessitates minimum up and downtime periods of several hours, and requires a significant minimum load reduction threshold. They are typically activated manually (i.e., phone call), can be scheduled for the next day, a few hours, or, at best, several minutes. Ramping is not controlled and the sustained curtailment period is typically 2- to 3-hours.

In contrast, the flexible loads associated with Bitcoin mining display unparalleled responsiveness, with response times measured in seconds and no prescribed minimum up and downtime. These loads possess a unique ability to curtail their energy consumption for indefinite durations while experiencing only a linear decrease in their economic output. Furthermore, ASICs can be deliberately and instantaneously under- or over-clocked, potentially providing an additional power quality management enhancement tool beyond traditional options (Naderi et al., 2018).

Conventional datacenters exhibit lower interruptibility due to the need to maintain uptime guarantees, reliance on wired internet infrastructure, lack of portability and modularity, and the requirement for controlled datacenters in specific locations. Real-time rendering of high-performance computational loads cannot be interrupted in the manner that trillions of successive, independent SHA-256 circuits can be. However, traditional high-performance compute and newer generative artificial intelligence workloads exhibit increased opportunity for flexibility at very large scale (Dodge et al., 2022).

Bitcoin mining, while not without its environmental implications, possesses distinct attributes that differentiate it as an industrial consumer. These attributes enable Bitcoin miners to compete effectively against conventional generation resources in providing ancillary service products to grid operators at a reduced cost. Notably, one of the primary attributes is the inherent interruptibility of Bitcoin mining loads, allowing for prompt and extended curtailment of energy usage. This flexibility positions Bitcoin miners to provide real time load balancing, seamlessly integrated into grid operations.

Demand response dynamics

The classification of ancillary services supplied to wholesale grid operators spans various categories, distinguished by deployment speed, response frequency, and activation duration. These categories include regulation reserves (up/down) and contingency reserves (spinning/non-spinning). Regulation services involve rapid and precise control or capacity provision to maintain continuous balance between generation and load under normal conditions. Spinning reserves respond within seconds to minutes, acting as contingency resources for rapid adaptation to unexpected drops in generation. It is worth noting that the evolution of DR over time highlights how loads, initially considered minor contributors to grid stability, have evolved into valuable resources, akin to traditional dispatchable generation resources.

The range of curtailment products offered by Bitcoin miners encompasses both generic DR services and specialized ancillary service products such as regulation and contingency reserves. These miners can function as controllable loads, capable of modulation in alignment with the energy and reliability requirements stipulated by grid operators. During winter storm Elliot (Dec 2022), responsive reserve service (RRS) obligations covered only a portion of power needs during the storm event (Figure 2). Large Flexible Load (LFL) consumption – Bitcoin miners – curtailed electricity-use sharply in advance of the storm, and almost completely during the time of peak electricity needs, when system prices spiked. In the wake of peak electricity prices during the storm, mining came back online in steps over the next two days.

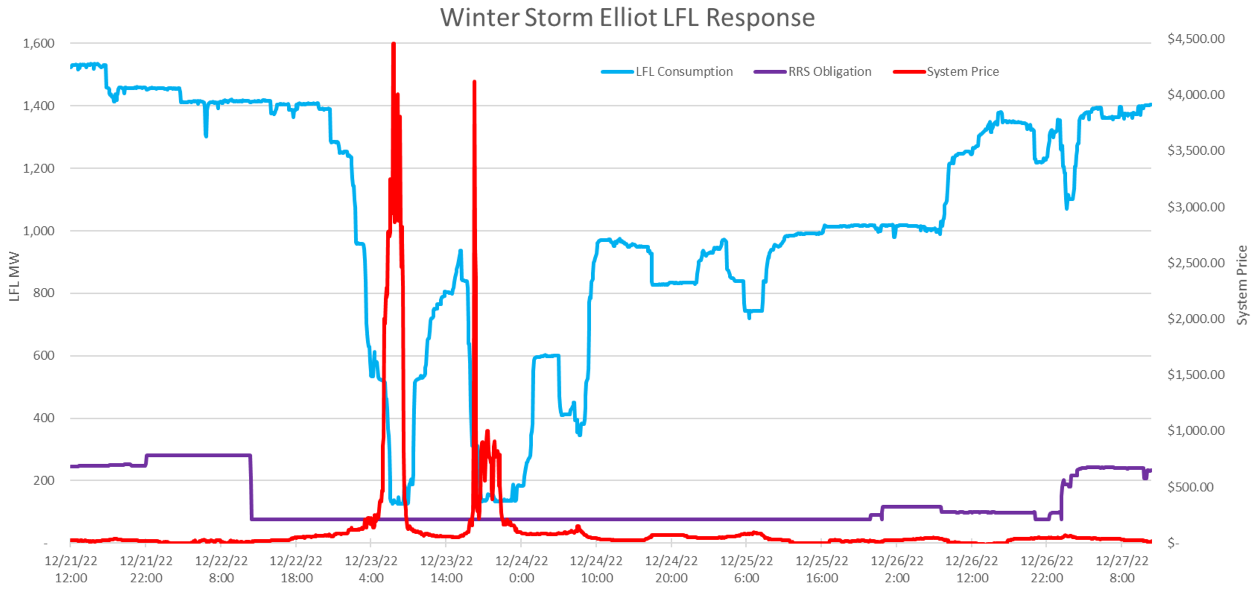


Figure 3. ERCOT curtailment by large flexible loads (LFLs – light blue line) in response to market price spikes (red line) during winter storm Elliott in December 2022 (summary report and chart available at www.ercot.com/files/docs/2023/02/21/7-Review-of-Winter-Storm-Elliott.pdf).

Bitcoin miners: implications for grid stability and ancillary services

The presence of flexible load resources like Bitcoin miners can yield both environmental and economic benefits. Unlike traditional generation resources, which need to be ramped up and down or operated inefficiently, flexible load resources can modulate demand directly. This capability not only has the potential to reduce carbon emissions (Rhodes et al., 2021) but also offers grid operators a more economically viable option. Traditional generation resources often operate below capacity for significant periods when fulfilling ancillary service obligations. In contrast, load resources compensate industrial entities for the opportunity cost of downtime, making them more economically viable from a grid operator's standpoint.

Among ancillary services, the distinct characteristics of Bitcoin miners stand out. They offer faster response times compared to equivalent forms of generation and can adjust their power draw with finer granularity, enhancing both configurability and responsiveness. Bitcoin miners primarily contribute to grid stabilization through demand modulation rather than altering supply dispatch. For instance, reducing 1MW of controllable load or increasing 1 MW of power demand both affect the power supply similarly. However, increasing 1 MW of power typically leads to heightened emissions from fossil fuel generation. In contrast, reducing 1MW of load does not increase emissions, as no additional power is brought online. Essentially, the controllable load being dispatched down reallocates that MW to the new load coming online.

From a financial perspective, Bitcoin miners offer a competitive edge in providing ancillary services. Traditional thermal power plants often require compensation for operating below maximum efficiency, leading to higher costs for grid operators. In contrast, Bitcoin miners are compensated for their opportunity cost, the revenue they miss out on during non-operational times. This generally results in load resources being a more cost-effective choice for grid operators. Importantly, when not participating in ancillary service provision, load resources like Bitcoin miners don't face lost income opportunities. This is in stark contrast to traditional power plants, which must choose between regular electricity generation and selling ancillary services, potentially missing out on revenue.

FERC supports this perspective, emphasizing that the pricing of ancillary services is based on the highest marginal opportunity cost incurred by any given resource (FERC, 2021b). Load resources typically incur lower opportunity costs during non-use compared to traditional generation resources. As a result, Bitcoin miners, being sophisticated and flexible loads, are becoming a preferable choice. They offer enhanced grid flexibility, thereby reducing the traditional reliance on dispatchable thermal generation for ancillary services.

Bitcoin miners in the ERCOT grid

The appeal of ERCOT for Bitcoin miners

ERCOT's wholesale grid stands out for its expansive and competitive nature, housing diverse retail markets that empower consumers to select electric providers based on various pricing models, ranging from index pricing to fixed block and index options. This adaptability particularly appeals to sophisticated industrial consumers who can curtail usage during scarcity events when electricity rates surge. This strategy grants them access to power at spot rates, optimizing cost efficiency.

The ancillary services market in ERCOT offers substantial economic incentives to Bitcoin miners. As Texas operates as an isolated grid, it must fulfill power system flexibility demands within its boundaries. Consequently, the ancillary service market in ERCOT holds greater economic significance per kWh produced compared to other RTOs/ISOs. This conducive environment supports miners' eligibility to participate in the market and augment their economic prospects.

Texas boasts abundant solar and wind resources, allowing for significant VRE penetration with competitive capacity factors. ERCOT ranks second in gross installed solar capacity and leads in wind capacity in the USA (www.spglobal.com/commodityinsights/en/market-insights/latest-news/electric-power/020821-ercot-solar-generation-output-doubles-continues-to-have-most-us-wind-output). Its reliance on wind and solar generation surpasses that of any other ISO/RTO (www.powermag.com/ferc-tackles-modernization-of-u-s-power-markets/).

Despite ERCOT's intraregional transmission, it frequently contends with negative pricing and curtailment events, especially in West Texas (emp.lbl.gov/renewables-and-wholesale-electricity-prices-rewep). Wind generation's expansion, buoyed by production tax credits, has led to negative pricing occurrences in regions like the Permian basin, where wind and solar plants coexist alongside limited transmission capacity (Seel et al., 2021). Negative pricing results from the combination of abundant wind generation and production tax credits that incentivize wind producers to offload power at a loss of up to $30/MWh instead of curtailing.

Texas Bitcoin miners have rapidly expanded the scope of mining operations and by Quarter 4, 2022, accounted for 43.6% of USA hashrate (climate.mit.edu/posts/climate-impacts-bitcoin-mining-us). This expansion was driven by factors aligning with Bitcoin miners' operational requirements. Leveraging the distinctive features of the ERCOT grid, Bitcoin miners positioned themselves as flexible load resources that enhance grid stability and adaptability. Their operational focus on fully computational processes provides the ability to exert precise control over power consumption, facilitating rapid adjustments. Bitcoin miners, being location-independent, portable, and capable of temporary installations, tap into stranded energy resources at various times and locations. The unique attributes of the ERCOT grid coupled with Bitcoin miners' capabilities forge a symbiotic partnership, illustrating the potential of Bitcoin mining to bolster renewable energy integration and grid optimization.

The appeal of Bitcoin miners for ERCOT

The prevalence of VREs and the scarcity of interconnections in ERCOT have driven the emergence of a dynamic ancillary services market and ERCOT has enthusiastically embraced Bitcoin miners as a valuable service provider for meeting its flexibility needs. Engaged in fully computational processes, Bitcoin miners wield precise control over power consumption, enabling swift adjustments. These miners' portability, location-independence, and ability to set up temporary installations align with ERCOT's high VRE penetration and limited interconnections, fostering a thriving and rapidly evolving ancillary services market that taps into both generation and load for power system flexibility. While many Bitcoin miners participate in DR initiatives, certain miners in ERCOT qualify as controllable load resources (CLRs). These CLRs manifest in two forms: controllable and non-controllable loads.

Controllable loads, exemplified by Bitcoin mining datacenters, exhibit high responsiveness and can precisely modulate their demand. Such loads serve the provision of ancillary services, promptly responding to ERCOT's frequency and energy requirements set through software control systems. Unlike mere load-shifting based on economic incentives, these controllable loads are directly managed by ERCOT itself. Their participation enriches the ancillary services market, bolstering grid flexibility and stability.

Bitcoin miners, operating as highly interruptible loads, are uniquely suitable for fulfilling the CLR designation. These datacenters hold the distinction of being the first load resources to satisfy ERCOT's CLR criteria, thereby becoming eligible to sell into any ancillary services market. This marks a significant leap in flexibility compared to conventional non-controllable loads participating in DR. ERCOT's nodal protocol rule revision for Load Resource engagement in Security Constrained Economic Dispatch (SCED) was introduced nearly a decade ago in 2013, and, until recently, no industrial load met the technical requirements to achieve the coveted controllable load resource designation. Today, Bitcoin mining datacenters uniquely fulfill ERCOT's prerequisites for sophisticated, responsive controllable loads.

While our focus centered on the USA, particularly the ERCOT grid in Texas, the insights derived indicate that Bitcoin mining's influence might extend beyond specific geographical regions and in markets characterized by varying degrees of regulation and decentralization. The symbiotic relationship between ERCOT's attributes and Bitcoin miners' adaptability not only fosters renewable energy integration but also hints at applicability of Bitcoin mining in grid optimization possibilities globally.

Conclusions

In the rapidly evolving realm of energy systems and grid management, the significance of DR and flexible load resources is more pronounced than ever. Our review highlights the emergence of Bitcoin miners as a potentially unique and adaptable load category. With their innate interruptibility and swift response capabilities, these miners may offer revolutionary potential for grid flexibility. Moreover, the capacity to monetize stranded and waste gas, coupled with the enhanced economics for renewable energy sources, may position Bitcoin mining as an important tool for helping to reduce carbon emissions.

Historically, DR's journey has evolved from a peripheral grid stabilization tool to a core provider of ancillary services. This trajectory, enriched by a detailed classification of ancillary service products and their economic benefits over traditional generation resources, sets the stage for understanding Bitcoin mining's seamless integration with grid operations. Bitcoin miners' ability to offer stable, quickly adjustable power consumption, combined with geographical adaptability, distinguishes them as premium controllable loads. This is exemplified by their characterization as the 'ultimate interruptible load' (Mellerud, 2021).

The experience within ERCOT suggests that Bitcoin miners can play an important role in DR, thereby bolstering both the technical and economic stability of the grid. This, in turn, could foster an environment for the further rapid expansion of VREs within the Texas grid. The extensive wholesale market and notable VRE penetration in Texas further create a favorable setting for Bitcoin miners, enhancing their appeal as prime controllable load resources because of their capacity to within seconds fine-tune power consumption.

The global momentum towards renewable energy sources accentuates the importance of flexible load resources for grid stability and resilience (FERC, 2021b; IEA, 2023; IRENA, 2018). Bitcoin mining addresses challenges posed by VRE sources and simultaneously offers economic and environmental advantages. However, Bitcoin's future energy consumption trajectory remains uncertain. If Bitcoin's market size parallels that of investment gold, its energy demands could soar. This potential surge necessitates a thorough examination of Bitcoin's direct and indirect effects on energy grids, power pricing, and emissions goals.

The comprehensive impact of Bitcoin on global energy demand and climate change remains complex, with emerging data suggesting its effects might be more nuanced than conventionally believed. As the narrative around Bitcoin mining evolves, in-depth analyses will be critical for discerning its future role in our energy transition. It is imperative for power market professionals, researchers, and policymakers to understand and remain cognizant of the potential role that Bitcoin mining may play as mining industry scope and scale advance.

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