Economic integration of Bitcoin mining in renewable energy and grid management

18 July 2024

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Abstract

This paper examines the potential role of Bitcoin mining in enhancing electricity grid stability and supporting the integration of variable renewable energy (VRE) sources. The integration of VRE, such as solar and wind, into electrical grids poses significant challenges due to their intermittency and often remote locations. Solutions like grid interconnections, dispatchable generation, advanced energy storage, and demand response (DR) mechanisms are essential to manage these challenges. Bitcoin mining, with its flexible load characteristics, has emerged as a highly adaptable load that can quickly adjust electricity consumption, making it an ideal participant in DR programs and a contributor to grid reliability. By applying comparative statics, we explore how Bitcoin mining affects supply and demand dynamics in electricity markets, stabilizing prices and improving VRE economics. The economic synergies between Bitcoin mining and VRE producers are highlighted, demonstrating how consistent energy demand from mining can drive investment in renewable infrastructure. Additionally, the environmental implications of utilizing waste energy for mining and the policy implications for encouraging such integrations are discussed. Our findings suggest that Bitcoin mining can reduce renewable energy curtailment, provide economic benefits to VRE producers, and lower overall electricity prices for consumers. We suggest that Bitcoin mining can play a key role in the transition to a sustainable energy future by enhancing grid stability, promoting renewable energy use, and supporting economic viability.

Keywords

Bitcoin mining; renewable energy integration; demand response; grid stability; energy economics; ancillary services

Introduction

The integration of variable renewable energy (VRE) sources, such as solar and wind, into electrical grids poses significant challenges due to their inherent intermittency and often remote locations. Solutions such as grid interconnections, dispatchable generation, advanced energy storage, and demand response (DR) mechanisms are essential to manage the variability of VRE supply [1-5]. The International Energy Agency (IEA) highlights the critical need to expand DR capacity to 500 GW by 2030 to meet the ambitious 2050 Net Zero Scenario [6]. Despite their potential, DR implementations are currently limited, comprising only 0.5% of total generation [7], while conventional generation—mainly thermal and hydro plants—provides 85% of available flexibility [8].

Bitcoin mining, characterized by energy-intensive data centers, has emerged as a highly adaptable load that can enhance the economic performance of VRE, support DR strategies, and improve grid stability [9-11]. Bitcoin miners can quickly adjust their electricity consumption, offering distinct advantages for grid management. Counterintuitively, the intensive energy use of Bitcoin mining may support VRE expansion by monetizing surplus energy during periods of high production and low demand.

In this paper, we review the potential role of Bitcoin mining in enhancing electricity grid stability and supporting the integration of VRE sources. By applying comparative statics, we explore how Bitcoin mining affects supply and demand dynamics in electricity markets. The flexible load characteristics of Bitcoin mining enable it to participate in DR programs and provide ancillary services, contributing to grid reliability and reducing the curtailment of renewable energy. The economic synergies between Bitcoin mining and VRE producers are highlighted, demonstrating how consistent energy demand from mining can drive investment in renewable infrastructure.

Additionally, we discuss the environmental implications of utilizing waste energy for mining and the policy implications for encouraging such integrations. This paper aims to stimulate thinking about the economic principles of supply and demand as they apply to Bitcoin mining, and how these insights might inform policies and investment strategies for a sustainable energy transition and grid stability. We suggest that Bitcoin mining can play a key role in the transition to a sustainable energy future by enhancing grid stability, promoting renewable energy use, and supporting economic viability.

Comparative statics

Market-clearing conditions

This paper employs 'comparative statics' to illustrate core economic concepts, applying supply and demand principles to assess changes in market-clearing conditions. Figure 1 provides a generic aggregate supply and demand framework for this analysis, showing various supply (marginal cost = MC) and demand (marginal benefit = MB) curves, and the impacts of changes in supply and demand on market price and quantity in a competitive market.

Consider moderate levels of supply ($s_{moderate}$) and demand ($d_{moderate}$) in Figure 1, where aggregate supply and demand curves intersect and define a market-clearing equilibrium with market price, $p_{(m,m)}$, and quantity traded, $q_{(m,m)}$. The demand curve is downward sloping—indicating that lower prices spur consumption—while the supply curve, based on the summation of marginal cost curves of individual suppliers, is upward sloping, indicating that higher market prices stimulate increased production. Although comparative statics can also explore changes in economic welfare—consumer and producer surplus—this paper focuses on directional shifts in supply and demand curves, not the overall dollar value of changes or benefit distribution.

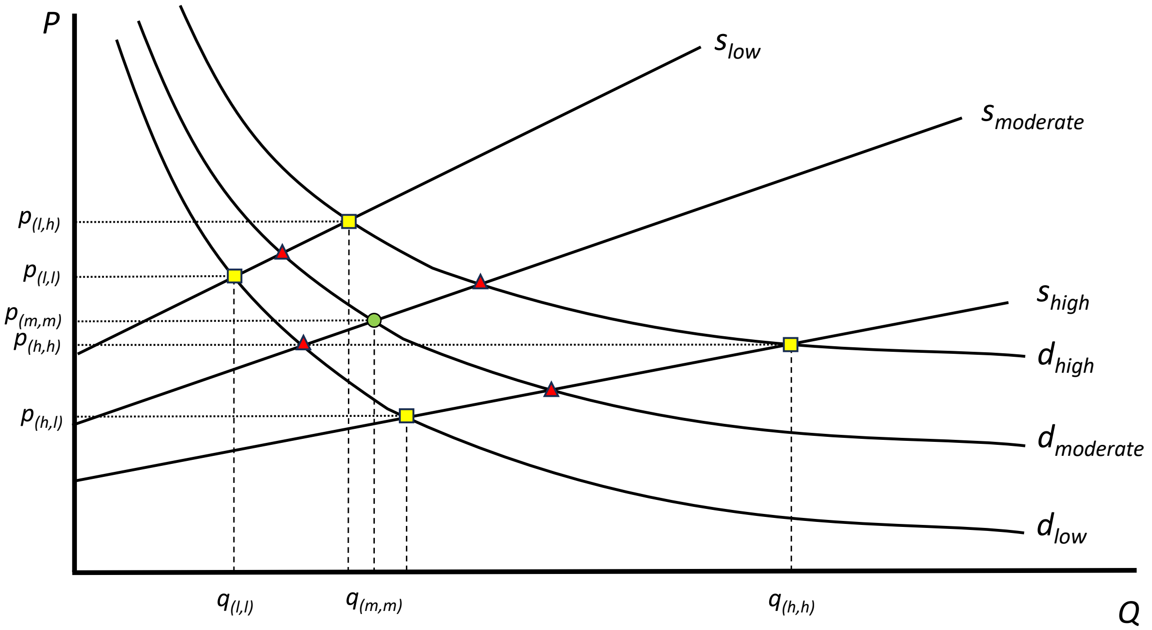

Figure 1. Impacts of shifting aggregate market demand and supply on equilibrium market price and quantity. Notation: y-axis P = market price; x-axis Q = quantity traded; s_{low}, $s_{moderate}$, and s_{high} = supply (MC) curves; d_{low}, $d_{moderate}$, and d_{high} = demand (MB) curves; $p_{(i,j)}$ and $q_{(i,j)}$ are equilibrium prices and quantities traded for supply level i and demand level j (for chart clarity, not all price and quantity levels shown). The green circle is the equilibrium point for moderate supply and demand levels; yellow squares mark the extremities of market price and quantity for various combinations of changes in supply and demand.

Supply and demand curves can shift inward or outward for various reasons. Given steady, moderate market demand, a decline in supply (s_{low}), represented by a leftward or inward shift in the aggregate supply curve, results in lower trade volume and higher market prices. Conversely, an outward expansion of supply (s_{high}), due to reductions in production costs, leads to increased trade volume and lower market prices. On the demand side, a reduction in consumer demand (d_{low}) with steady, moderate supply results in lower quantity traded and lower prices, while an increase in demand (d_{high}) results in higher quantity traded and higher prices.

When both supply and demand curves shift simultaneously, some directional moves in price and quantity can be predicted (e.g., an increase in both supply and demand always leads to higher volumes traded), while other combinations may lead to uncertain net impacts. The trapezoid delineated by square markers in Figure 1 defines the range of possible combinations of equilibrium market price and quantity for simultaneous shifts in supply and demand curves.

Firm-level production decisions

In competitive industries, the intersection of aggregate supply and demand determines the market-clearing price and quantity. However, individual firms are price takers, meaning their production levels do not affect equilibrium prices (Figure 2). The quantity produced by each firm is determined solely by the market price (denoted as p^*, which defines their marginal benefits) and their own MC curve.

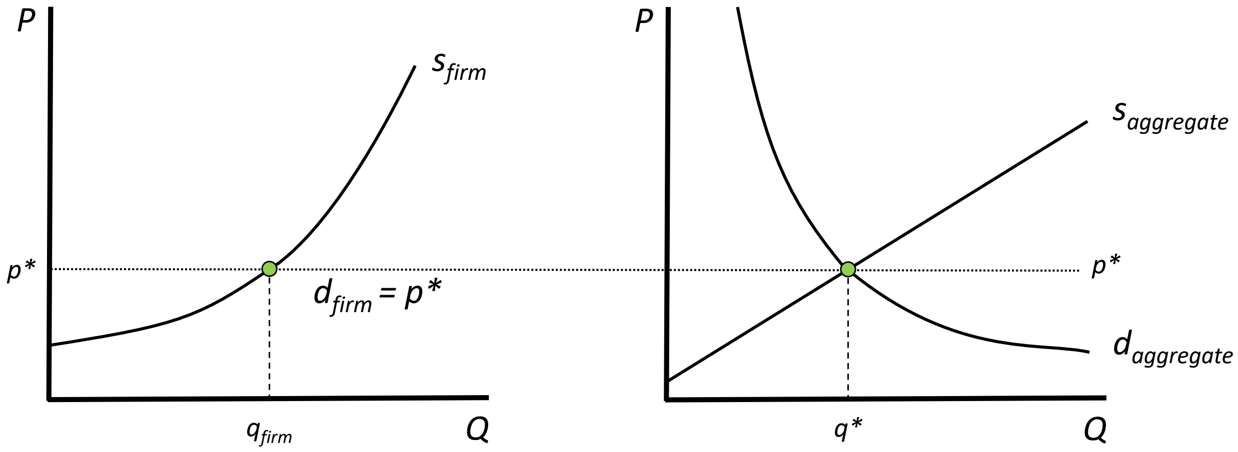

Figure 2. Equilibrium market-clearing price in a competitive market defines the MB (= demand) curve for an individual firm. A firm chooses their production level based on their own unique cost of production (MC curve) and the market-clearing price (*p**) set in the overall market.

Variability in firm production

Different firms have different MC curves, resulting in varied production decisions. To illustrate, consider three firms with different MC curves (low, moderate, and high cost) (Figure 3). The firm with the highest marginal cost of production would be priced out of the market, as MC > p* (MB), leading them to stay idle to avoid losses. The low- and medium-cost producers make production choices based on their MC of production. The total amount produced is the sum of the quantities produced by the low-cost, moderate-cost, and high-cost producers.

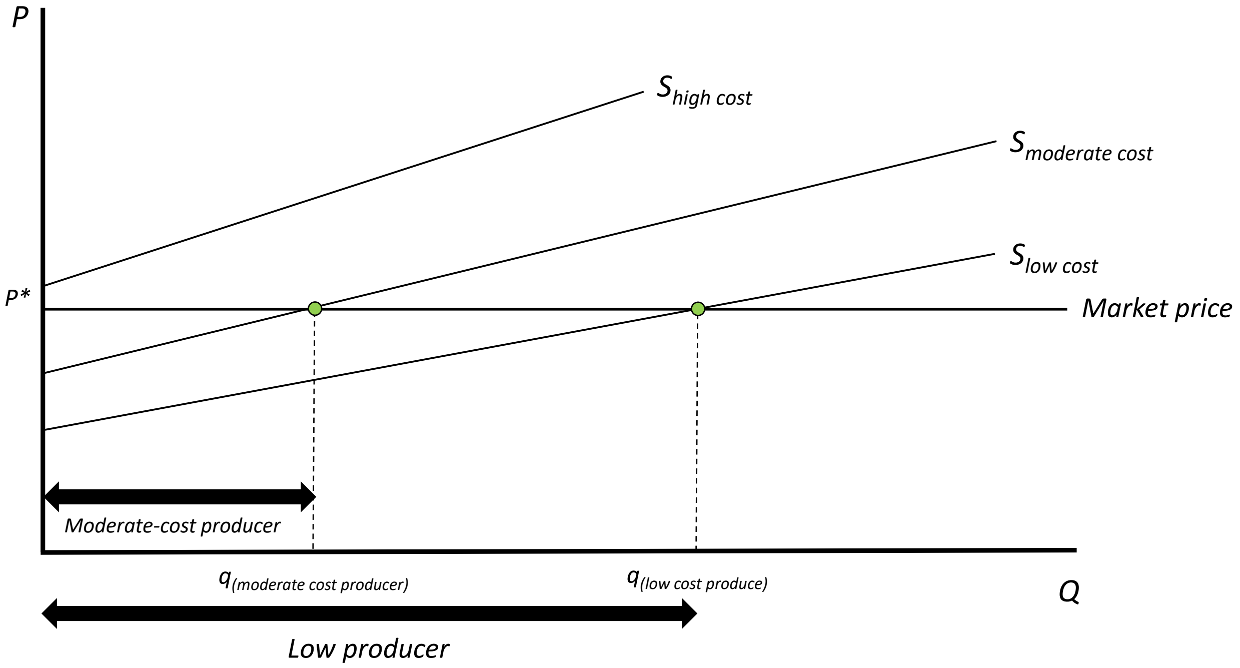

Figure 3. Production quantities from three firms that vary in their marginal cost (MC) profiles and face constant market prices (=MB) determined in a large, competitive market.

Variable renewable energy (VRE)

Challenges and growth of VRE

The ambitious integration of low-carbon sources, particularly solar and wind, into global power grids is gaining momentum. From 2010 to 2020, global wind capacity expanded by an average of 14% annually, reaching 743 GW and comprising 6% of the global power mix [12]. In 2021, wind and solar represented 90% of the new electric generating capacity planned in the USA and 75% globally (www.seia.org/solar-industry-research-data). Wind energy could account for 18.8% of global production by 2030 [13], with the Global Wind Energy Council envisioning a 30% share by 2050 [12]. By 2050, VRE could constitute 60% of China's power mix and 80% in the United States [2].

The integration of solar and wind energy into the power grid exemplifies the complexities inherent to VRE generation sources. These sources have daily and seasonal intermittency, as well as location-specific constraints [14, 15]. For example, the best areas for wind farms may be in or adjacent to mountain ranges, far from urban markets or industrial hubs. Economic curtailment, firms ceasing production when market price falls beneath their marginal cost of production becomes increasingly pertinent as the contribution of VREs to the energy mix escalates [16, 17]. In the United States, the rapid deployment of new wind and solar installations, widespread use of financial incentives for VRE expansion, and associated transmission infrastructure constraints have led to frequent curtailment (Figure 4).

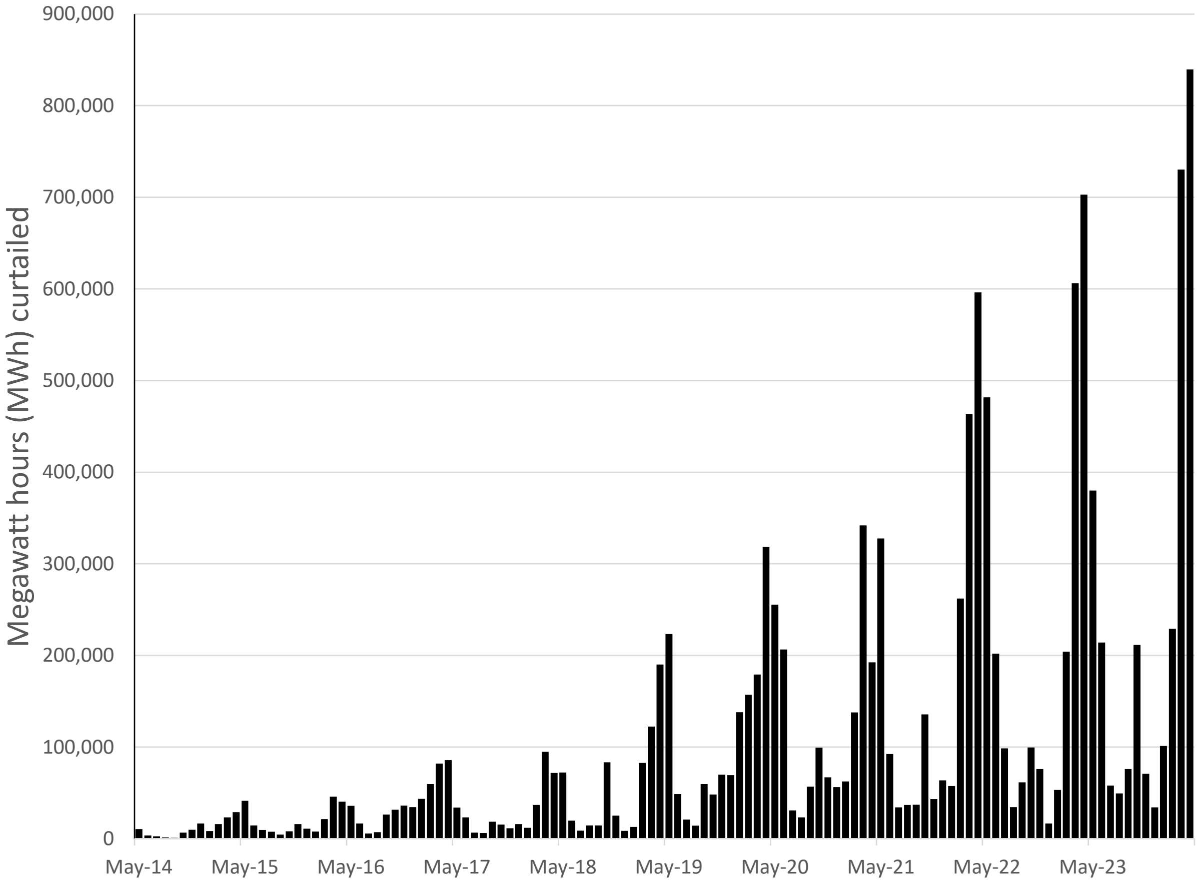

Figure 4. CAISO VRE curtailments in California (www.caiso.com/informed/Pages/ManagingOversupply.aspx).

Rapidly expanding VRE production capacity in the USA has increasingly resulted in negative wholesale pricing episodes for producers [18]. Instances of negative pricing accounted for 6.3% of all hours in 2022 across U.S. wholesale market nodes (Figure 5), underscoring the implications of added wind and solar capacity in regions like Texas, known for its favorable wind speeds and solar irradiance but constrained by limited transmission capabilities [17, 19].

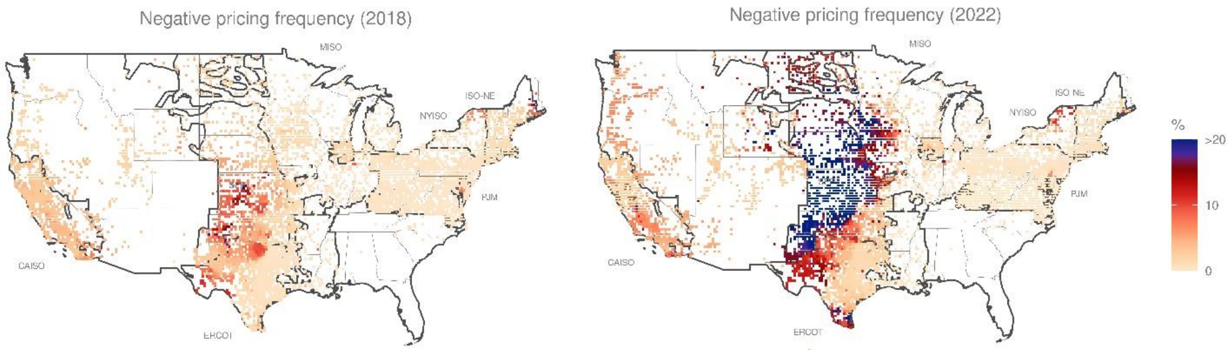

Figure 5. Negative electricity pricing in the USA in 2018 (left) and 2022 (right) [20].

Economic and operational challenges of VRE

From an economics perspective, the marginal cost curves for VRE producers are falling as technology advances and economies of scale take hold, pushing the aggregate supply curve outward and leading to downward pressure on market prices (Figure 6). When there is also a decline in demand (e.g., at night in the short-run or due to increasing levels of conservation and efficiency in the long-run), this puts further downward pressure on market prices. The quantity produced under these conditions could be more or less than the original situation, depending on the shape of the curves and the magnitude of change, but market price would always be lower.

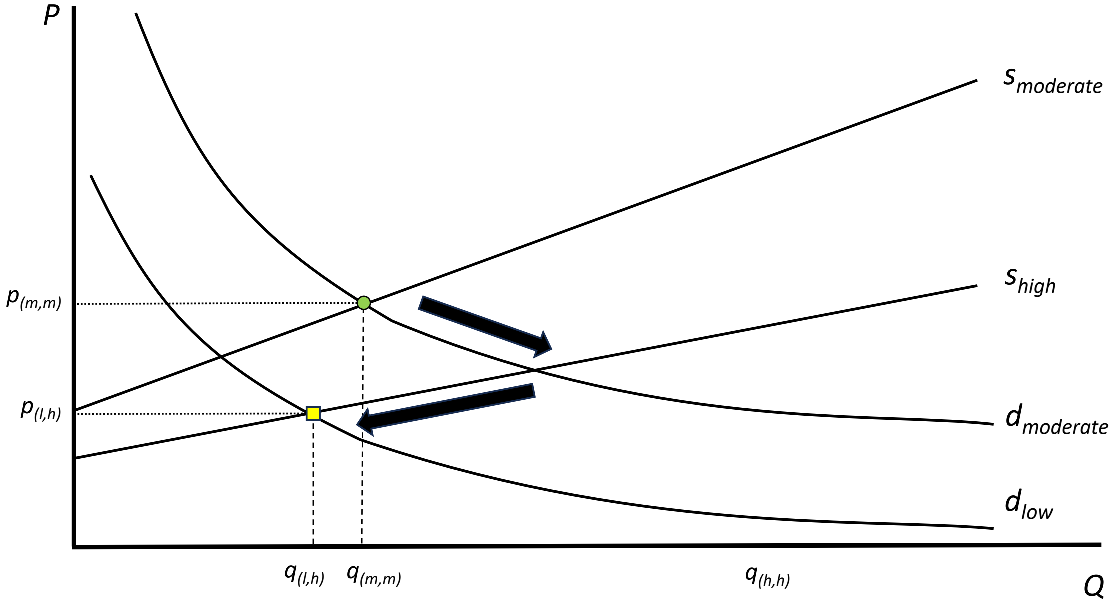

Figure 6. Market prices decline in the face of increasing supply and falling demand.

Grid operators must balance VRE's intermittent generation with stable electricity demand. During periods of high generation and low demand, VRE can cause grid instability, requiring curtailment to maintain system reliability. Curtailment results in lost economic opportunities for VRE producers and can deter future investments [18].

Market impacts of VRE curtailment

Lower prices can lead to a sequential series of curtailment (Figure 7). A downward move in market-clearing equilibrium price will price both moderate- and high-cost producers out of the market at some point (sometimes called the strike price, but not to be confused with what that means in options markets) It also causes the lowest-cost producers to reduce their output. Recall, individual firms are price-takers in competitive markets, so their decision regarding production levels is based solely on market price and their own cost structure. They will sequentially shut down as prices fall and come back online as prices rise, with all decisions based on their marginal production costs.

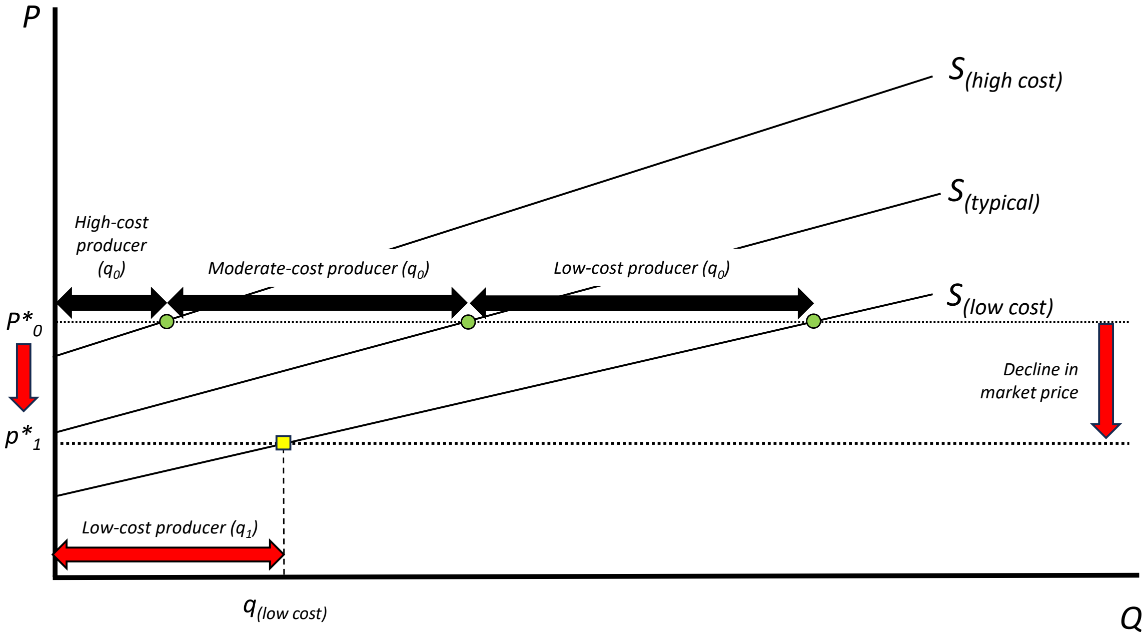

Figure 7. Market equilibrium price decline impact on three firms with different marginal costs of production (hollow arrows): after the price decline, only the low-cost producer would be supplying a reduced amount of electricity to market (solid arrow).

Impact of subsidies on VRE market prices

Subsidies can increase the market price for VRE-generated electricity: VRE firms increase production more than they would in the absence of a price subsidy; consumers reduce their consumption at the higher price; and the government agency funding the subsidy absorbs part of the electricity production cost (Figure 8). Subsidies are commonly used in emerging strategic industries to help firms establish themselves and stabilize the industry over time. However, subsidies can be habit-forming, making their removal controversial (e.g., periodic milk-dumping protests by French farmers in Paris). Economically, VRE firms continue producing electricity to capture incentives during periods of high production and low market demand, as long as marginal benefits, including subsidies, exceed marginal costs. Depending on the supply and demand curves and the subsidy size, this can sometimes lead to negative pricing when market demand falls to very low levels.

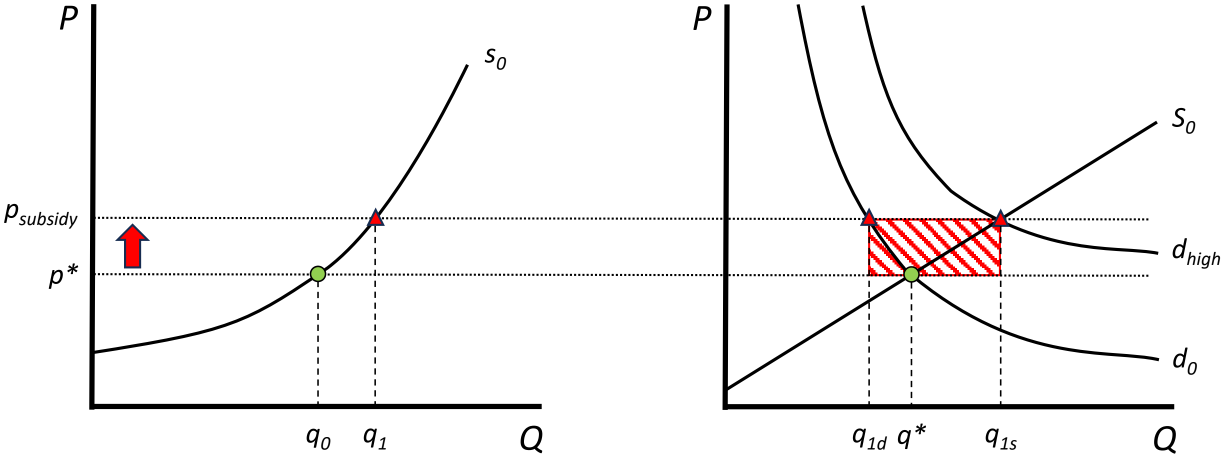

Figure 8. Price dynamics with a subsidy. Assumptions: an agency pays a subsidy for electricity producers (to improve profitability and increase production capacity); individual firms receive more ($p_{subsidy} - p^*$) for their electricity, incentivizing them to expand production (left panel); at the aggregate level, extra supply enters the market (q_{1s} total production), and, for producers, the subsidy has the same impact as an increase in market demand to d_{high}; with the subsidy, however, electricity consumers reduce their consumption at the new higher price; and firms receive more ($[p_{subsidy} - p^*]*[q_{1s} - q_{1d}]$) for higher-than-equilibrium production levels. Funders – government agencies – pay a fee to increase industry profitability (red hatch), potentially leading to overproduction and stifled demand if subsidization becomes normalized.

Enhancing power system flexibility

The International Energy Agency (IEA) underscores the equal importance of both flexible demand and supply in the energy transition (www.iea.org/articles/energy-transitions-require-innovation-in-power-system-planning). Interconnections between electricity networks can import energy from grids with varying generation patterns, thereby contributing to system flexibility. However, these interconnections currently account for only 5% of global grid flexibility [7]. In areas with isolated grids, such as Texas, the absence of these interconnections limits grid flexibility. Conversely, interconnected regions benefit from the ability to export surplus power to markets with higher demand.

Battery storage at VRE facilities can mitigate supply challenges by extending the availability of solar-generated electricity into nighttime hours. Rapid advancements in grid-scale battery technology are expected to play a crucial role in the near future. Maintaining system frequency, which must stay within a tight range around 60 hertz, is another key challenge for grid operators. VRE's sporadic generation adds complexity (https://www.caiso.com/documents/flexibleresourceshelprenewables_fastfacts.pdf).

To address the unpredictability and fluctuations inherent to VREs, regional transmission organizations (RTOs) and independent system operators (ISOs) with high VRE penetration are implementing reforms to enhance operational flexibility. In the USA, organizations like CAISO, Midcontinent Independent System Operator (MISO), Electric Reliability Council of Texas (ERCOT), and Southwest Power Pool (SPP) have introduced new ancillary service products. These products aim to provide short-term ramping capabilities, essential for managing the dynamic demands imposed by increasing VRE contributions. These efforts represent a broader industry recognition of the need for enhanced operational flexibility to ensure reliable service as the energy mix evolves to include more VREs and weather-dependent distributed energy resources.

Managing electricity grid supply and demand

Supply-side strategies

Supply-side strategies in grid management focus on adjusting the generating capacity. These strategies target the supply curve (Figure 9) by introducing additional supply when necessary. Grid managers can influence the market price of electricity through subsidies or fees, thereby controlling the amount of electricity available in the market.

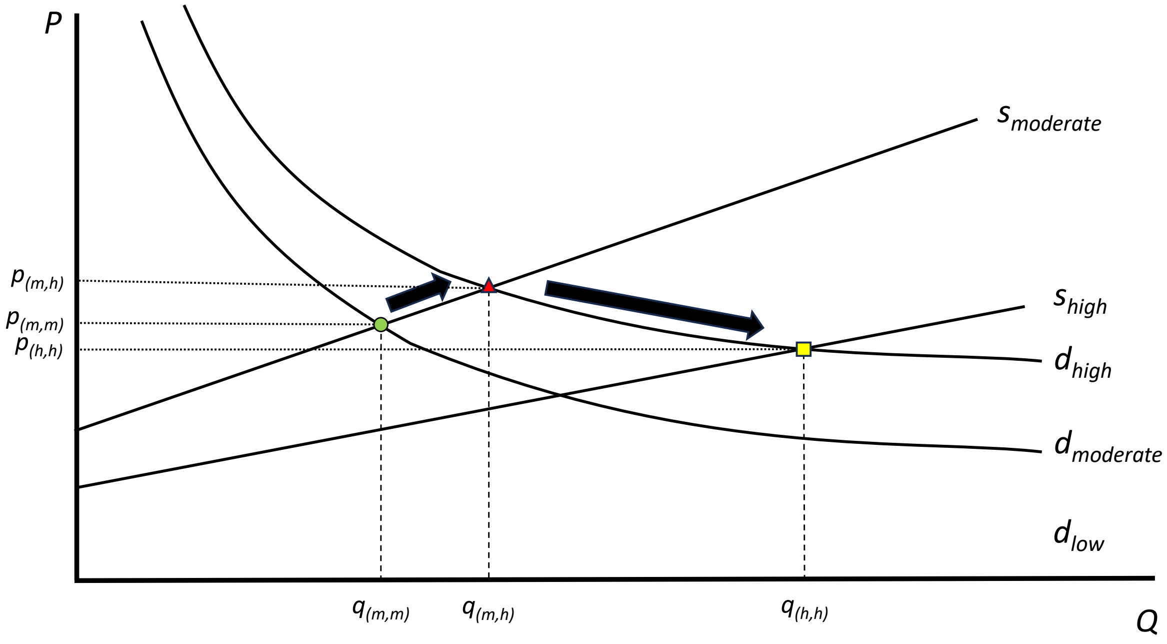

Figure 9. Increasing supply to control electricity market price increases during periods of high demand. Initially, market demand increases to $p_{(m,h)}$ (red triangle). Electricity producers respond based on their current MC, increasing the quantity of electricity available to $q_{(m,h)}$. The relative magnitude of the price increase to consumers depends on the shapes of the supply and demand curves. To reduce market prices, regulators need to offer price incentives or subsidies to electricity producers. In this chart, a subsidy equal to the difference ($p_{(m,h)}$ - $p_{(h,h)}$) would induce extra production online, increase the supply of electricity to the market, and lead to lower prices.

Electricity suppliers respond to shifts in market demand that raise the equilibrium market price: economically marginal suppliers will come online, supplying the extra electricity needed as the market price, their marginal benefit, exceeds their marginal costs of production. For instance, oil-fired peaker plants may be used for short periods to meet peak demand. These plants typically have the highest marginal costs of production, so they are only activated when market demand drives prices high enough to be profitable.

While market forces can induce extra production as demand rises, complications can arise if market-based pricing leads to harmful outcomes, such as life-threatening conditions during extreme weather events. In Texas, electricity prices can spike to thousands of dollars per MWh during peak demand, extreme demand scenarios, and poor VRE generation conditions [21]. During the June 2022 Texas heatwave, wind generation fell to about 25% of normal on June 20, causing price spikes. Conversely, prices during the record-setting demand on June 26 and 27 were much lower due to normal windy conditions (Figure 10).

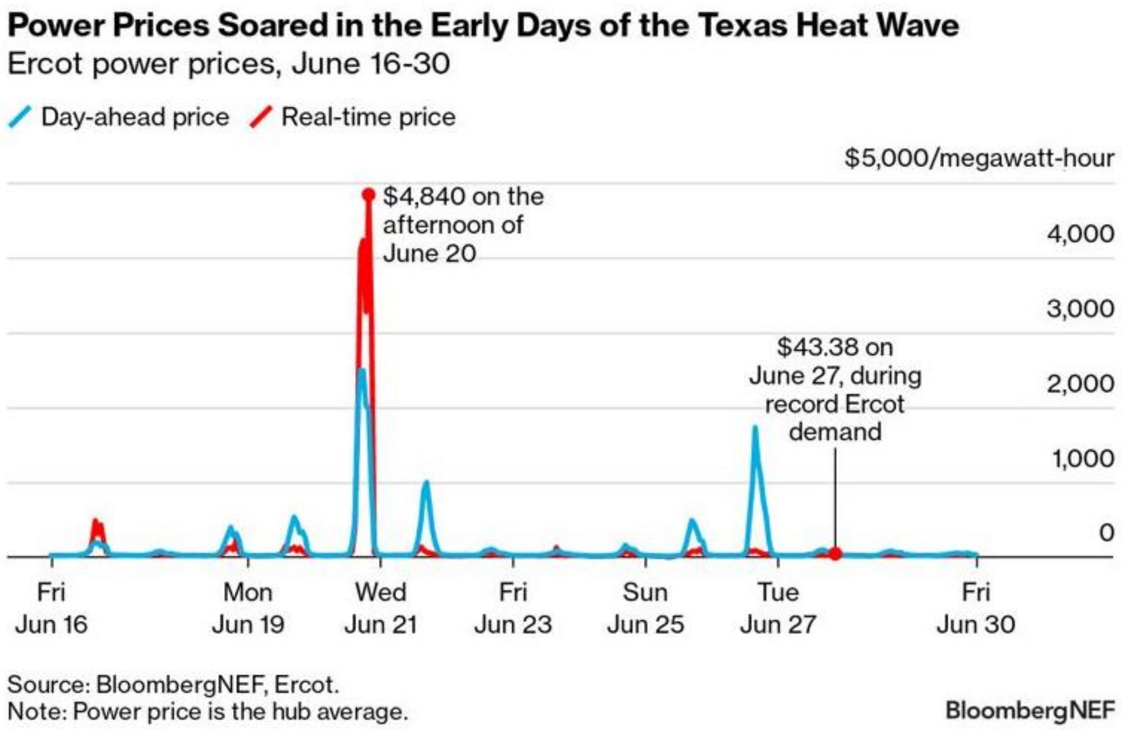

Figure 10. ERCOT pricing during June 2022 heat wave (source: https://about.bnef.com/blog/scorched-texas-sees-1-7-billion-in-power-sales-in-one-day/)

Some media articles have highlighted Bitcoin mining companies profiting when the Texas grid was stressed and retail prices were high (https://www.texastribune.org/2024/01/03/texas-Bitcoin-profit-electricity/). However, some articles omit to mention that power had been pre-purchased under contract from ERCOT.

In the case of pre-payments, the situation is akin to an industrial bakery locking in flour prices in advance. If a drought destroys the wheat crop elsewhere, causing wheat and flour prices to spike, the bakery might find it more profitable to sell their pre-paid flour than produce bread. Both the bakery and Bitcoin mining operations benefit economically from selling their core input when market conditions make it advantageous. Futures contracts, established for agricultural products in the mid-1800s (https://eh.net/encyclopedia/a-history-of-futures-trading-in-the-united-states/), are critical for firms wanting to hedge against input price fluctuations and product sales.

Consider a hypothetical power market with six different types of producers (Figure 11): VRE wind and solar (lowest marginal costs); hydroelectric and nuclear (slightly higher marginal costs); and various thermal generation options with escalating costs, with oil-fired peaker plants having the highest marginal cost. The market's supply curve will be kinked [a 'merit order' spot market - see 22]. During periods of full VRE supply and moderate demand, the entire electricity supply would come from lower-cost VRE producers and hydroelectric and nuclear facilities.

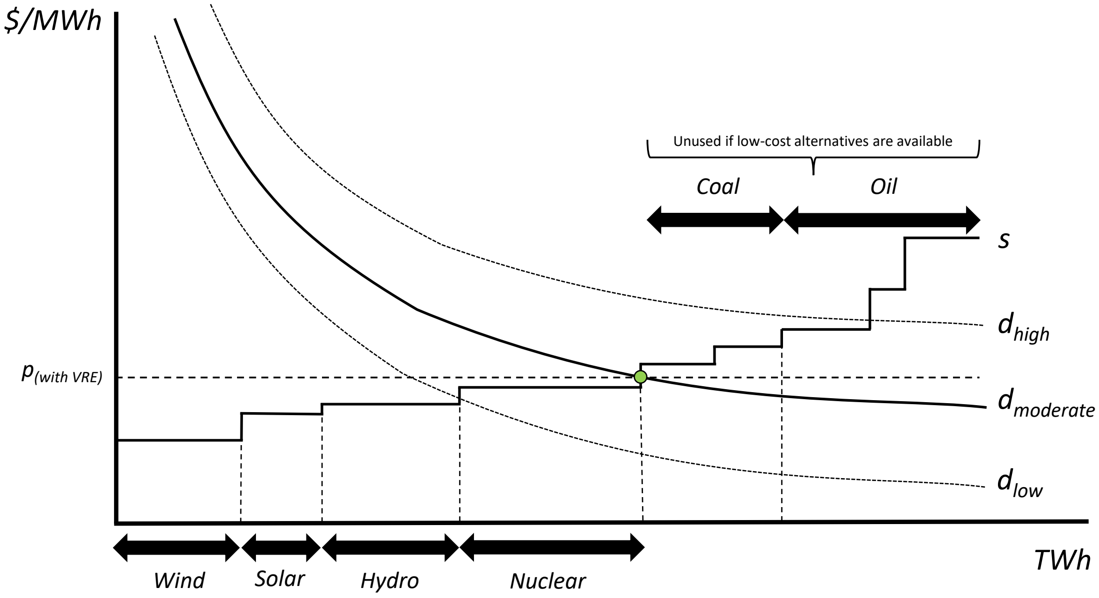

Figure 11. Aggregate electricity supply (MC) curve for a hypothetical market with distinct energy types and technologies that vary in their sectoral production costs.

When VRE electricity is unavailable (e.g., on a calm night), the supply curve shifts inward, making coal and some oil-fired production economical at moderate demand levels. During high demand periods (e.g., a very cold, calm night), firing up peaker plants may become necessary (Figure 12). In extreme events, such as the June 2022 Texas heatwave or early-2024 winter storms, maximum grid electricity generation capacity might be exceeded. In such cases, the supply curve becomes vertical at maximum capacity, and market price is solely determined by market demand and consumers' willingness to pay extreme prices.

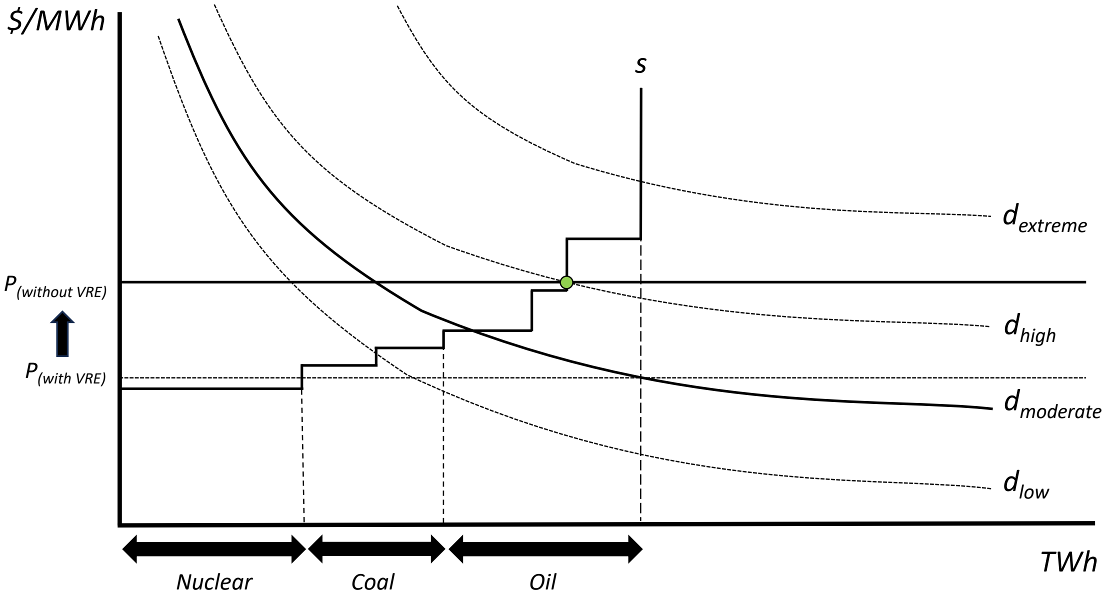

Figure 12. The kinked supply curve shifts horizontally inward to reflect the loss of intermittent VRE. With typical market demand, a small amount of thermal electricity would be needed. If market demand is high, oil-fired peaker plants may be needed. If maximum production capacity is reached during extreme demand, the supply curve turns vertical, and market price is determined solely by the intersection of market demand and the fixed level of supply.

With the deployment of new wind and solar facilities and substantial expansion of VRE capacity, renewable energy might cover 100% of supply at moderate demand levels, with nuclear or fossil-fuel generation needed only for higher demand (Figure 13).

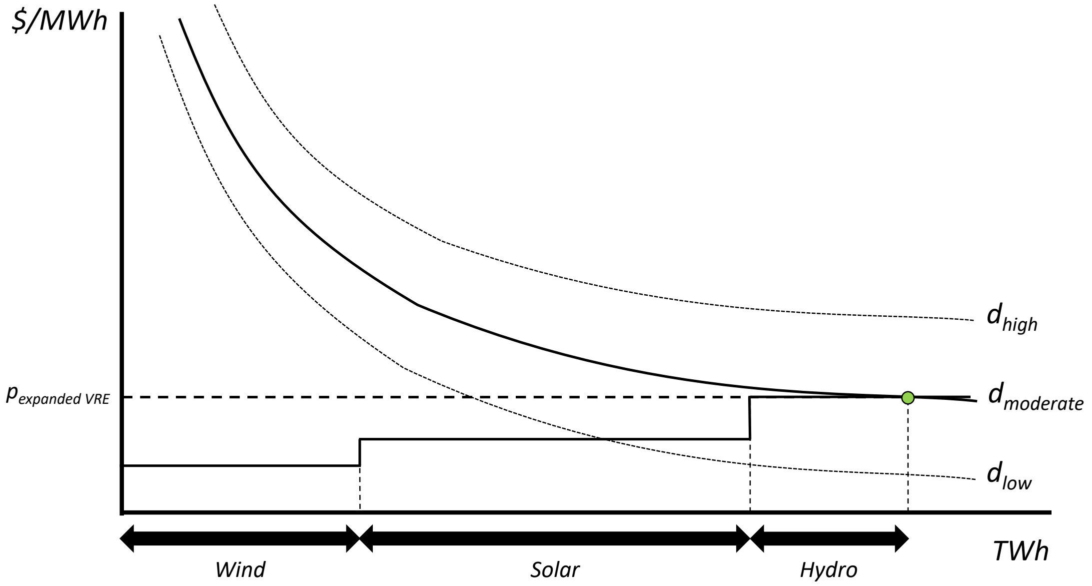

Figure 13. Increasing production from low-cost VRE producers pushes the aggregate supply curve outwards, pricing coal and oil generation out of the market under moderate demand conditions.

Base load considerations

One key consideration for grid electricity supply is the role of base load supply. Large-scale hydroelectric and nuclear facilities may produce electricity with low marginal costs but require substantial investment up-front and offer little operational flexibility to adjust to shifting market conditions. Long-term power purchase agreements (PPAs) may be in place, guaranteeing minimum price levels for these facilities. If VRE facilities can supply electricity at similar scales, curtailment may still be necessary, or grid-scale energy storage technology must be installed to balance the flow of electricity from multiple sources. For VRE to act as a base load supplier, completely negating the need for fossil fuel, VRE facilities would have to be massively over-built, with sufficient generating capacity and battery storage to ensure power supply during the most extreme conditions. That level of VRE infrastructure would imply a high level of idle VRE facilities when demand was low to moderate (just as fossil fuel peaker plants sit idle today, waiting for extreme supply or demand shocks).

Advances in battery storage technologies are significantly impacting some electricity grids. For example, the current state of technology allows for large-scale battery charging from solar power in California and discharging for up to about four hours after sunset, during peak early-evening demand (Figure 14). The yellow area of the chart represents solar energy generation during daylight hours, while the light green area shows battery discharge during the evening. Battery storage helps flatten VRE supply by extending the duration of solar-generated electricity availability. This technology is rapidly expanding in the CAISO region [23] and includes electricity trading with other ISO/RSOs.

To eliminate carbon emissions, a country must maximize output from low-cost VRE facilities, small- and large-scale hydroelectric, nuclear generation, and battery storage. It becomes apparent how complex grid management can quickly become with diverse PPAs and multiple generation options.

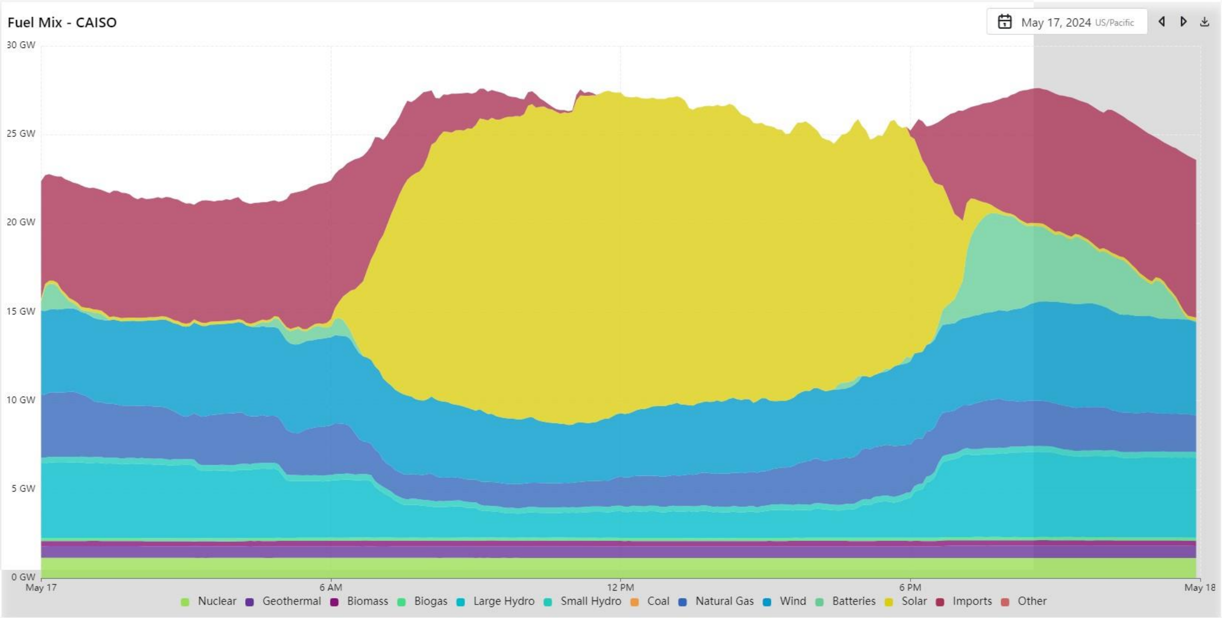

Figure 14. Electricity supply (https://www.caiso.com/TodaysOutlook/Pages/supply.html) for the California grid on May 17, 2024. Daily data is available for seven USA major RTOs/ISOs at: https://www.gridstatus.io/graph

Retail demand

Retail time-of-use demand response (DR) initiatives are designed to encourage the shifting of electricity usage to off-peak periods by altering market prices to influence consumer behavior, enhancing grid functionality and reliability. Such retail DR programs employ advanced metering infrastructure, including smart meters, which achieved a 60% penetration rate in US households by 2019 [24], to monitor and manage residential and commercial electricity usage. This allows consumers to adjust their electricity usage in response to time-of-use billing, taking advantage of lower rates during off-peak hours. The emergence of demand aggregators and virtual power plants bolsters this ecosystem [25, 26]. Despite the complexity of real-time energy pricing, localized curtailment signals are crucial in optimizing DR effectiveness for alleviating grid congestion.

Economically, these programs aim to modify the demand curve, influenced by variables such as household income and electricity costs. They stimulate demand by lowering electricity prices when excess power is available, or curb demand by raising prices during periods of scarcity, employing sophisticated tiered pricing strategies that may vary by consumer segments (e.g., different income levels, where electricity use might range from essential services like heating to luxury uses) (Figure 15).

Industrial demand pricing strategies

Since the 1970s in the USA, DR has evolved from a marginal grid stabilization tool to an essential resource, akin to dispatchable generation. The aim is to integrate 500 GW of DR capacity globally by 2030, a significant increase from 50 GW in 2020 [6]. Demand-side management, encompassing both retail and wholesale DR programs (accounting for 62.7 GW in 2019 and covering 8.3% of the US summer peak load [24]), enhances grid flexibility and stability across industrial, commercial, and residential sectors. Industrial loads particularly benefit from wholesale DR programs, which adjust consumption patterns to align more closely with supply dynamics [3].

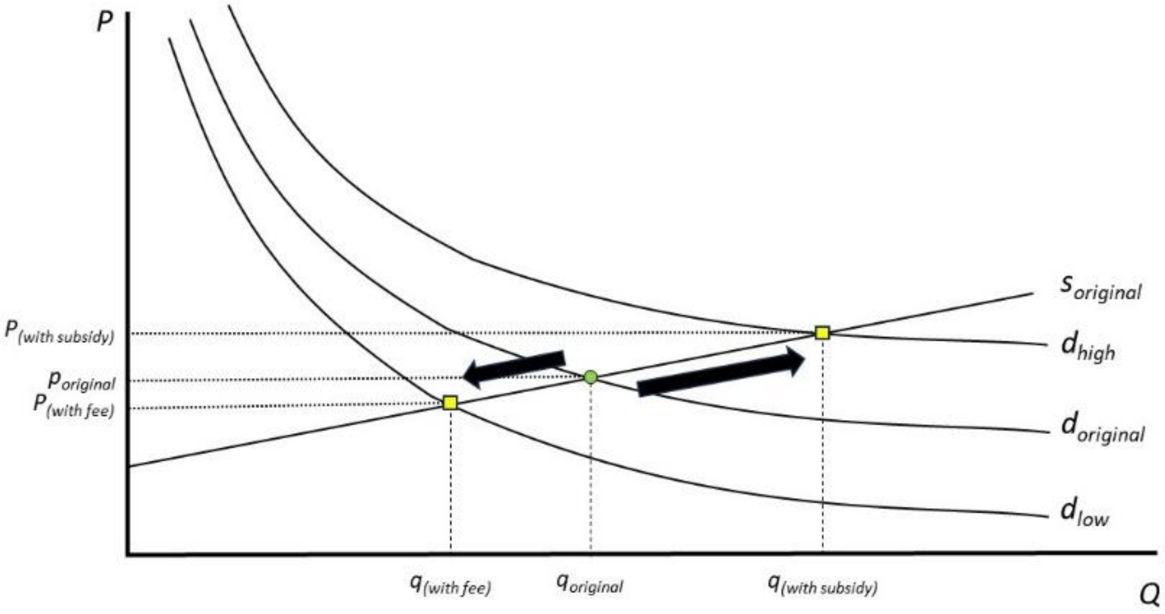

Figure 15. Impacts of changing the market price of electricity from market equilibrium to a prescribed price: subsidizing (increasing) the price stimulates consumption and production levels, while penalizing (taxing) consumption reduces price and consumption level.

Industrial demand response can employ tiered pricing strategies that may encourage off-peak consumption in sectors capable of 24/7 operations, potentially using differential rates leveraged by inflexible power generators like hydroelectric or nuclear facilities (Figure 15 also applies here).

Industrial consumers often secure long-term supply through PPAs with ISOs/RSOs, locking in prices and reducing business uncertainty while ensuring predictable revenue for electricity producers and grid operators. Alternatively, they may opt for day-ahead or real-time markets, and utilize a range of financial instruments like futures and options available on exchanges such as the CME.

Industrial demand controllable loads

Controllable loads represent a sophisticated DR strategy that enables real-time industrial electricity use adjustments based on grid operator dispatch instructions. These loads can autonomously adjust consumption in response to grid frequency fluctuations, significantly enhancing grid flexibility—vital for integrating the growing penetration of variable renewable generation [4, 27]. In contrast, non-controllable loads might be disconnected entirely by grid operators during critical periods. ERCOT's advanced DR applications enable real-time energy consumption adjustments in response to grid requirements (https://www.ercot.com/services/programs/load/laar).

Economically, controllable load strategies typically permit industrial operations to run at full capacity during normal conditions but require reductions during periods of high retail demand (e.g., during extreme weather events). Controllable load strategies help moderate industrial demand to stabilize market prices (similar to retail strategies shown in Figure 15).

Electricity customers outside controllable load agreements react to price signals by reducing usage when costs exceed marginal benefits. Controllable load agreements offer cost benefits to producers, who receive lower rates in exchange for operational flexibility during peak conditions, and to grid operators, who gain precise tools for balancing supply and demand.

Not all industrial loads are suitable for DR programs, with their eligibility varying based on factors like energy intensity, response time, and geographic flexibility. The capacity for unscheduled interruptions differs widely among industrial processes, often constrained by potential economic or operational disruptions. The range of DR-eligible loads varies significantly, reflecting differences in responsiveness, availability, cost-effectiveness of response measures, granularity of consumption adjustments, and locational flexibility [28]. Energy-intensive industrial operations—such as electrolysis, grinding, heating, and cooling—present established sources of flexible loads. Yet, interrupting these processes poses direct risks to business continuity and financial performance.

Most industrial operations, including AI and cloud data centers, show limited tolerance for unscheduled downtime due to potential revenue losses, logistical disruptions, or equipment damage. Even in sectors amenable to interruptions, the feasibility of completely ceasing consumption remains limited. Thus, the inherent characteristics of physical industrial processes impose intrinsic limitations on the scope and feasibility of load flexibility.

Bitcoin mining: an economic overview

With foundational insights into electricity supply and demand now established, we can explore how Bitcoin mining fits into the broader context of electricity generation and consumption. This discussion aims to develop informed perspectives on the potential impacts of increasing Bitcoin mining activity on VRE production, market pricing, and grid management. Many effects, however, may not be immediately evident from first principles alone, necessitating later empirical research to clarify the supply and demand curves and to evaluate the efficacy of different policy measures on system efficiency—including aspects like producer and consumer surpluses, governmental revenues and subsidies, and deadweight losses.

The mechanics and economics of Bitcoin mining

Satoshi Nakamoto [29] synthesized pre-existing concepts within computer science and cryptography [30] to develop Bitcoin's proof-of-work consensus mechanism for a global, decentralized ledger system. Each time a new block of financial transactions is recorded (about 10-minutes), the miner who first solved a cryptographic guessing game wins the right to create the block. That miner gets a Bitcoin reward and the transaction fees for the block. This computational contest, among independent miners working on the world's largest computer network, embeds substantial real-world energy and computing costs into the digital record, making unauthorized alterations to the blockchain impossible. The fixed supply schedule of Bitcoin, capped at 21-million coins, creates a supply inelasticity where any shifts in market demand directly affect the equilibrium price. The periodic halving of Bitcoin issuance further constrains supply, putting upward pressure on prices as demand increases, and some coins are permanently lost (e.g., accidentally sent to non-existent wallet address, lost key phrases on discarded computers, etc.).

Economic characteristics of Bitcoin mining

Supply Rigidity

Miners cannot influence issuance rates (Figure 16), making the supply curve perfectly inelastic. Shifts in demand directly affect market-clearing prices, affecting miners economically ($q_0 * [p_h - p_m]$). The periodic halving events reduce new Bitcoin issuance, further limiting supply and increasing prices with growing adoption.

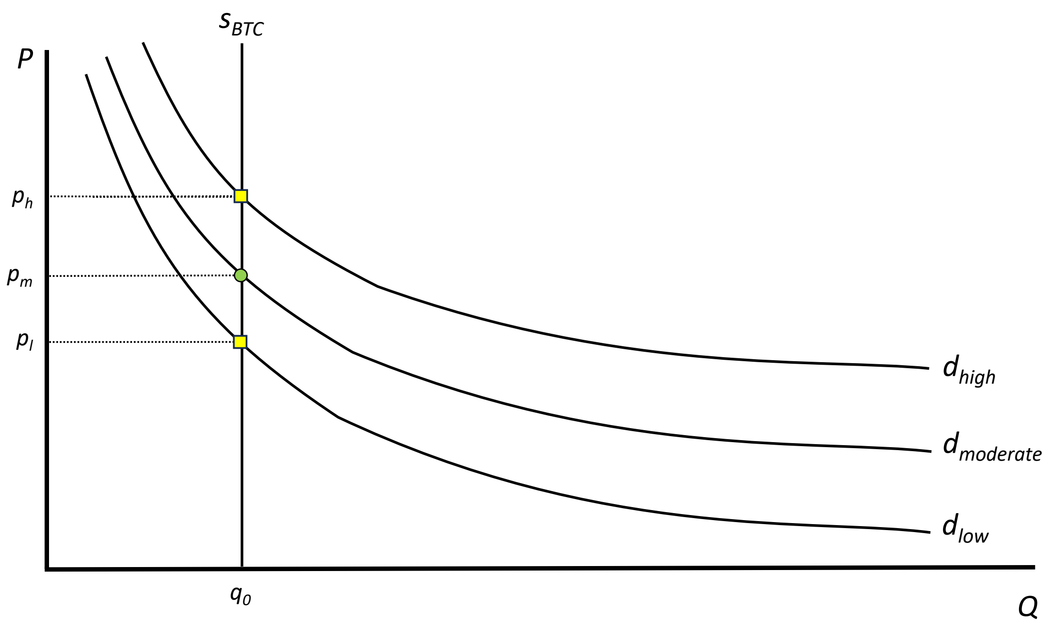

Figure 16. Impact of changes in market demand on equilibrium price in the face of perfectly inelastic supply. It may be easiest to conceptualize Bitcoin's fixed supply schedule by thinking about the supply curve shifting right or left as supply conditions change but with the curve itself being vertical because no amount of extra compute can accelerate the fixed issuance schedule. Long-term Bitcoin holders may decide to sell a portion of their held supply, which would also move the supply available right or left, but would not impact the inelastic nature of the asset.

Halving events:

Bitcoin issuance is systematically reduced, halving approximately every 210,000 blocks or about every four years, which gradually decreases the block subsidy size. This process of logarithmic decay, which will continue until around 2140, limits new supply entering the market, implying that any increase in Bitcoin adoption will likely exert strong upward pressure on market prices (Figure 17).

Mining competitiveness

The profitability of Bitcoin mining is dependent on several factors: the block subsidy (currently 3.125 Bitcoin per block until the next halving in 2028), average transaction fees per block, the difficulty adjustment (which recalibrates every two weeks to maintain an average block creation time of about 10 minutes), the market price of Bitcoin, and the total network hashrate. The formula for calculating Bitcoin hash price (USD per terahash per day) is given by:

$$p_h = p_{BTC}\left(s * \frac{86{,}400}{\left[{diffulty * 2^{32}}/{hashrate}\right]}\right)$$

where p_h = hashprice (US\$/terahash/day), p_{BTC} = Bitcoin market price (USD\$), s = block subsidy (3.125 Bitcoin/block in the current epoch, d = difficulty adjustment, and h = aggregate global hashrate.

Bitcoin price is determined in a global competitive market open to new entrants without barriers, as long as they can afford mining hardware and have access to electricity. Miners' expected returns on their investment depend primarily on their share of the global hashrate, Bitcoin market price, and their cost of compute, which is itself a function of electricity cost and the energy efficiency of their computer fleet. All miners are price-takers in the global Bitcoin marketplace: they face a horizontal demand curve and their decision to mine or shut down is based entirely on their own marginal cost of production (recall Figure 8).

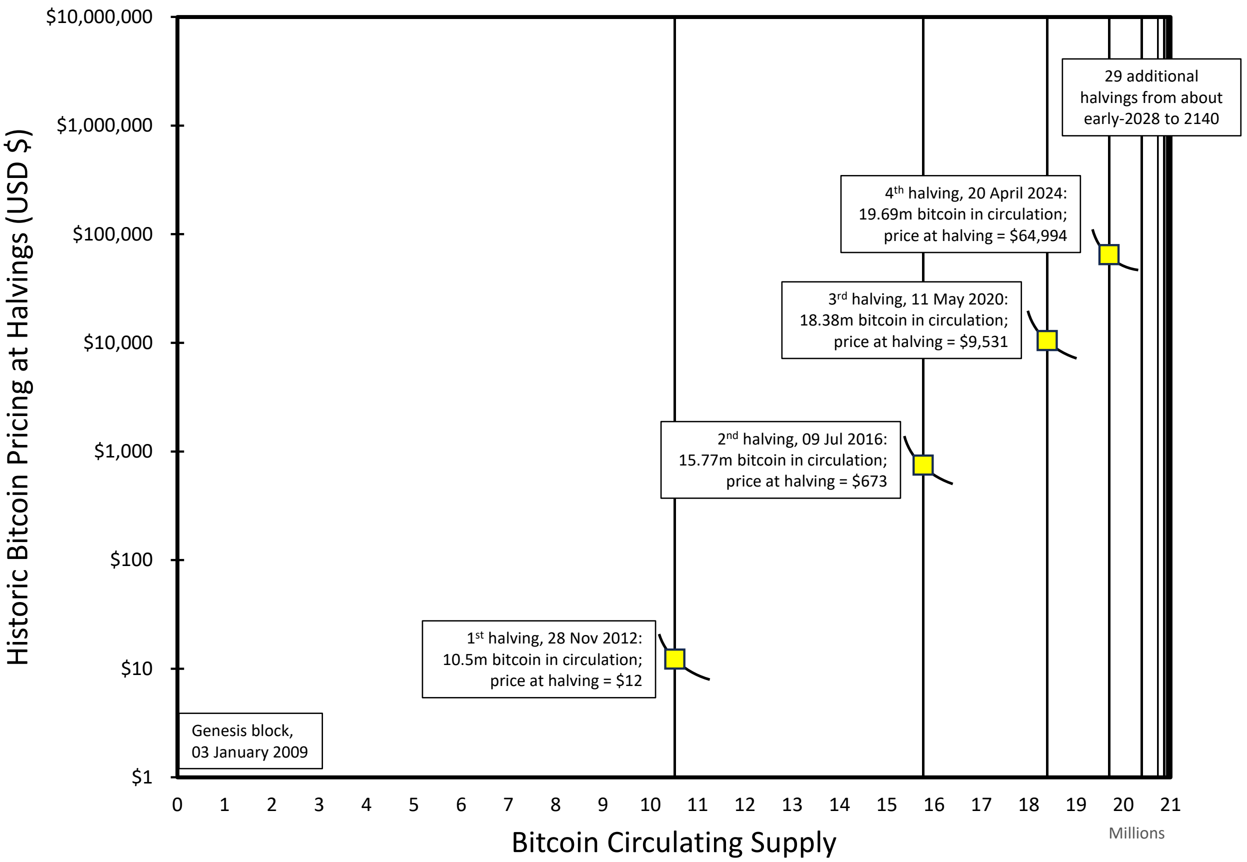

Figure 17. Circulating supply and market pricing trends across Bitcoin's halving events, illustrating demand curve shifts on halving dates (price data from statmuse.com).

Bitcoin miners' operations are highly sensitive to electricity costs, as evidenced by their willingness to shut down during periods of high electricity prices. For instance, in Texas, ERCOT has identified a 'strike price' at which mining becomes unprofitable (MC > MB). During the winter storm Elliott in December 2022, Bitcoin miners significantly curtailed their electricity usage in response to market price spikes, thereby aiding grid stability during critical demand periods (Figure 18).

Bitcoin mining is not only responsive to local market conditions but also subject to global competition. The intense competition in Bitcoin mining encourages miners to seek the lowest possible electricity prices and to explore economically beneficial byproducts such as low-grade waste heat (e.g., for district heating, greenhouses, timber drying) or carbon credits (e.g., methane destruction).

VRE sources like solar, wind, and geothermal are particularly attractive to Bitcoin miners due to their low marginal costs. Miners also increasingly utilize stranded or wasted energy sources, such as methane from landfills or vented natural gas from oil and gas operations [31]. Additionally, integrating Bitcoin mining with renewable biogas setups has shown potential for both economic and environmental benefits, aligning mining activities with sustainable energy generation [32].

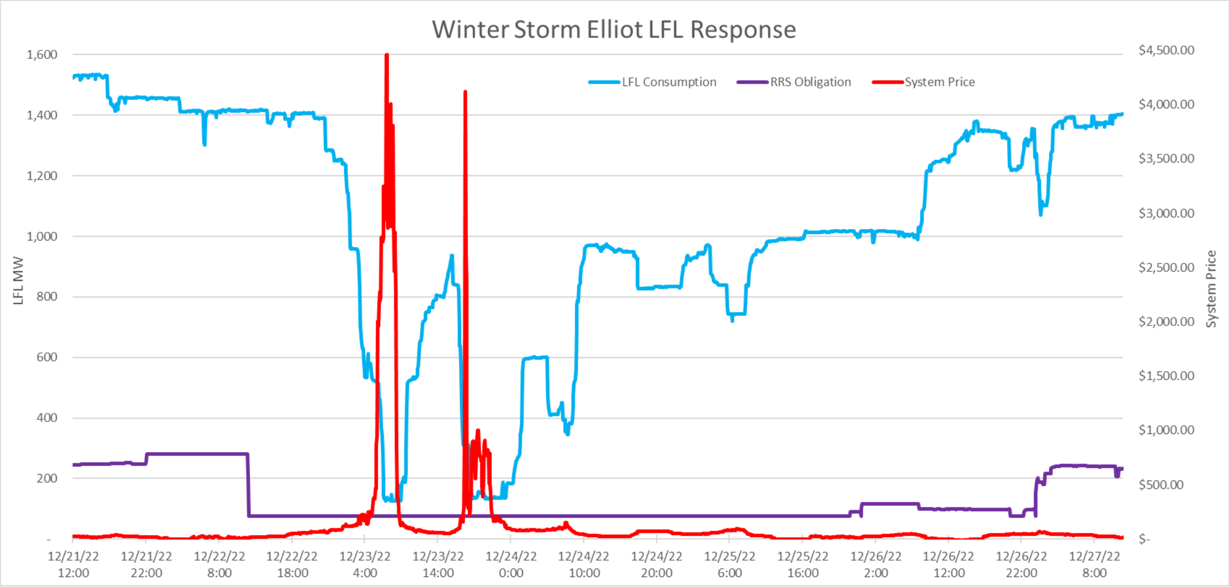

Figure 18 – ERCOT curtailment by large flexible loads (LFLs – light blue line) in response to market price spikes (red line) during winter storm Elliott in December 2022 (www.ercot.com/files/docs/2023/02/21/7-Review-of-Winter-Storm-Elliott.pdf).

Economic implications of Bitcoin mining

Benefits for VRE producers

Bitcoin mining provides a consistent demand for energy, reducing renewable energy curtailment and offering a novel monetization strategy [33]. For instance, wind farms have utilized Bitcoin mining as a strategy to hedge against the volatility of electricity prices [34]. Miners act as reliable consumers, allowing VRE operators to economically exploit unused energy. This relationship facilitates VRE production in locations still pending grid connections and infrastructure development, thus expediting investments, asset monetization, and grid balancing.

For VRE facilities, the continuous purchase of electricity by Bitcoin miners mimics the impacts of government setting a floor price for electricity, enhancing VRE producer revenues (Figure 19). When a government subsidizes electricity costs up to the floor price (if $p_i < p_{(\text{Bitcoin mining electricity})}$, then subsidy = $p_{(\text{Bitcoin mining electricity})} - p_i$] but in this case, the 'subsidy' incurs no costs to any government agency and is instead covered entirely by the competitive Bitcoin market.

Implications for electricity consumers

Contrary to popular belief. (e.g., https://www.texastribune.org/2024/01/03/texas-Bitcoin-profit-electricity), Bitcoin mining can lower overall electricity prices by enhancing VRE profitability and attracting new producers. The willingness of miners to pay for electricity, often at rates above local market prices, is influenced by the global price of Bitcoin.

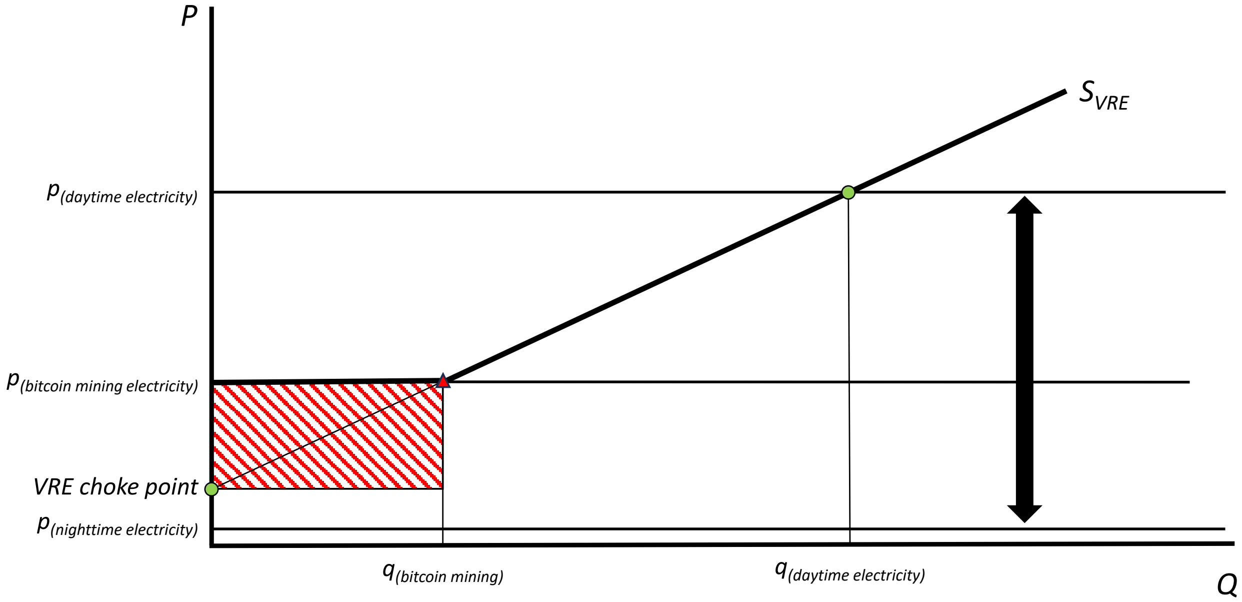

Figure 19. Supply curve for a wind VRE producer. In scenarios without a Bitcoin miner as a constant buyer, a wind producer might stop production during low-demand periods. With Bitcoin mining, the wind farm sells a quantity $q_{(Bitcoin\ mining)}$ of electricity, generating revenue represented by the red, hatched area and a producer surplus above the supply curve.

While concerns exist that high Bitcoin prices could price out traditional consumers, two main factors mitigate this risk:

1. **Global Competition**: The competitive nature of Bitcoin mining limits the duration of high electricity prices, as global competition drives miners to lower-cost energy sources, mitigating local price impacts. As Bitcoin prices rise, global entry into the mining industry increases, often in regions with lower energy costs, such as near stranded hydroelectric dams or remote VRE sites, reducing the likelihood of local price impacts.

2. **Market Supply Dynamics**: Increased revenues from Bitcoin mining enhance the profitability of VRE producers, likely attracting more players to the market and pushing the aggregate supply curve outward. This increase in supply tends to lower electricity prices for all consumers, making costly thermal generation less necessary except during extreme conditions (refer to Figure 9).

Governments aiming to cut carbon emissions benefit from maximizing VRE output. With enhanced profitability through Bitcoin mining, the need for fossil fuel generation diminishes, leveraging market forces to expand sustainable energy without direct government intervention. In markets where mining competes with other consumers and potentially raises prices during peak Bitcoin valuations, implementing PPAs that cap electricity access for miners could be a strategic measure, pending empirical studies to balance the benefits and costs of such mining activities.

Consequences for other energy producers

The mobility of Bitcoin mining was highlighted post-2021 following the industry's exodus from China due to regulatory bans, with many operations relocating to Central Asia and North America (https://www.forbes.com/sites/colinharper/2022/12/23/Bitcoin-mining-in-2022-the-year-boom-turned-tobust/). The mobility of Bitcoin mining operations allows them to pair with emerging VRE projects, absorbing surplus energy and enhancing economic viability. Miners can relocate as local grids develop, demonstrating a flexible, DR approach.

This adaptability also supports the economic capture of excess, off-grid energy from sources like remote hydropower or methane-emitting sites [35], converting waste into profitable assets. For instance, integrating mining operations with oil and gas facilities that vent or flare natural gas transforms waste into a profitable asset with minimal production costs. This not only makes marginal or inactive drilling sites more economically viable but also has environmental benefits by converting methane – a potent greenhouse gas [36] – into less harmful emissions. Note, however, that the overall impact on carbon footprints necessitates empirical research to weigh the costs and benefits of increased oil and gas usage against methane emission reductions.

Enhancing grid stability

Bitcoin miners, as flexible loads, enhance grid stability by participating in DR programs and providing ancillary services. They help balance demand fluctuations, reduce operational costs for grid operators, and lower electricity prices for consumers. Bitcoin mining offers rapid response capabilities and fine power adjustments, surpassing traditional generation in configurability and responsiveness.

Historically viewed as minor contributors, loads like those from Bitcoin mining have evolved into valuable grid resources, akin to traditional dispatchable generation resources. Unique to Bitcoin mining are its rapid response capabilities and fine granularity in power adjustments, which surpass traditional generation forms in both configurability and responsiveness. Bitcoin mining contributes to grid stabilization through demand modulation, reducing consumption rather than increasing supply, which is environmentally advantageous as it does not increase emissions.

From an economic standpoint, Bitcoin miners provide a cost-effective alternative for ancillary services. Bitcoin miners face no lost income opportunities, unlike traditional power plants that must choose between regular electricity generation and selling ancillary services.

Bitcoin miners' operational flexibility also allows them to seamlessly integrate into grid operations, unlike conventional and AI data centers that require stable power supplies for continuous operation (i.e., firms cannot shut down an AI datacenter for an unknown duration when there is an extreme weather event). This flexibility makes them ideal for participating in demand response initiatives and ancillary services, providing a valuable complement to existing and emerging grid solutions.

The ERCOT experience

ERCOT provides a favorable environment for Bitcoin miners due to its expansive, competitive market and substantial solar and wind resources in Texas (www.spglobal.com/commodityinsights/en/market-insights/latest-news/electric-power/020821-ercot-solar-generation-output-doubles-continues-to-have-most-us-wind-output) Texas leads the U.S. in VRE penetration and boast high-capacity factors in renewable energy production (www.powermag.com/ferc-tackles-modernization-of-u-s-power-markets/). The expansive wind generation in West Texas frequently results in negative pricing due to overproduction (emp.lbl.gov/renewables-and-wholesale-electricity-prices-rewep), further incentivized by production tax credits [18] that encourage wind producers to offload power at a loss of up to $30/MWh rather than curtailing it. This scenario creates an advantageous setting for Bitcoin miners, who can leverage the low or negative electricity prices to provide valuable grid services and monetize electricity that would otherwise be wasted.

ERCOT's unique market structure, characterized by diverse retail pricing models and a crucial ancillary services market, enables consumers to optimize cost-efficiency by adjusting usage during price peaks. As an isolated grid, ERCOT internally manages its flexibility needs, making its ancillary services market particularly significant. Bitcoin miners thrive in this environment, where their ability to act as Controllable Load Resources (CLRs) allows them to meet ERCOT's stringent technical requirements for real-time demand adjustment. This capability positions them to enhance grid stability and efficiency significantly.

During events like winter storm Elliott, Bitcoin miners in Texas reduced energy usage, aiding grid stability (https://www.ercot.com/files/docs/2023/03/27/December-2022-Cold-Weather-Operations-Public-Report.pdf). This proactive load management aligns miners' financial incentives with broader grid resilience goals, ensuring stability amid increasing frequency and severity of weather disruptions. This symbiotic relationship not only supports immediate grid operations but also forms a foundation for regulatory frameworks that could further incentivize Bitcoin miners' involvement in resilience planning and risk management, ensuring grid stability amidst increasing frequency and severity [37] of weather disruptions.

Conclusions

A successful global renewable energy transition needs flexible load resources for grid stability and resilience [3, 14, 38]. In this paper, we have explored the significant role Bitcoin mining can play in enhancing grid stability and economic efficiency within renewable energy systems, particularly those with high VRE penetration. The adaptability of Bitcoin mining operations positions them as vital flexible and controllable loads, capable of managing the intermittency challenges posed by VRE sources like solar and wind.

Innovative application of Comparative Statics

This study's application of comparative statics to analyze the economic dynamics of Bitcoin mining within the renewable energy sector represents a novel approach in Bitcoin research. Typically reserved for more theoretical analyses, employing comparative statics to derive policy-relevant insights into Bitcoin mining's role in energy markets showcases an innovative integration of economic theory with practical, real-world issues. This method has allowed us to elucidate the direct and indirect impacts of Bitcoin mining on supply and demand dynamics, providing a clearer understanding of its potential to stabilize markets and support the economic viability of renewable energy. Comparative statics is a valuable tool, capable of providing directional advice on strategic decisions in the increasingly intersected domains of energy economics and digital asset management. Future research could further refine these insights, offering more detailed guidelines for policymakers and stakeholders in the energy sector.

Enhancing grid stability and flexibility

The integration of Bitcoin mining into electricity grids, particularly those with high VRE penetration, offers substantial opportunities for enhancing grid stability and economic efficiency. Bitcoin miners' ability to rapidly adjust electricity consumption makes them valuable participants in DR and ancillary services, reducing reliance on fossil-fuel-based peaker plants and lowering operational costs for grid operators. Bitcoin mining's integration into grid management not only supports system reliability during variable supply and demand but also mitigates risks during extreme weather events, thereby enhancing grid resilience.

Economic viability and renewable energy expansion

Bitcoin mining creates economic synergies with VRE producers by serving as a stable, predictable load that can absorb excess electricity during low-demand periods. The consistent demand from Bitcoin miners supports the financial viability of VRE projects, driving further investment in renewable energy infrastructure. Such dynamics are pivotal in accelerating the transition towards sustainable energy sources and achieving broader societal goals of a stable and environmentally friendly energy grid.

Environmental considerations

While concerns about the environmental impact of Bitcoin mining persist [39-43], integrating mining operations with renewable energy sources and utilizing waste energy from off-grid resources significantly mitigates these issues [9-11, 31, 34, 44, 45]. This strategy not only leverages unused energy but also supports the reduction of greenhouse gas emissions, enhancing the overall sustainability of the mining activities.

Policy and investment implications

Policymakers and investors should recognize Bitcoin mining’s potential to support renewable energy integration, leveraging its flexibility and economic benefits to enhance VRE deployment and grid stability. Targeted research [46, 47], strategic investments, and informed policies can help foster market-driven growth in the renewable sector, reducing the need for government subsidies and making the energy transition more economically sustainable.

Bitcoin mining offers a unique and promising solution to the challenges associated with integrating VRE sources into electricity grids. By enhancing grid stability, supporting economic viability, and providing environmental benefits, Bitcoin mining can play a pivotal role in the transition to a sustainable and resilient energy future. Further research will be needed to optimize the integration of Bitcoin mining with renewable energy systems and to fully understand its broader economic, environmental, and social impacts.

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