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Feature

Renewable Energy Transition Facilitated by Bitcoin

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ABSTRACT: Reduction of greenhouse gas emissions has been a top priority for activists, scientists, and policy makers across the globe, and it is one of the main drivers for the transition to renewable energy generation. Bitcoin is a decentralized global transaction network of an eponymous digital currency. It has been praised for its openness, decentralization, and censorship resistance, as well as criticized for its inefficiency, criminal use, and enormous electricity consumption. We discuss the challenges in the renewable energy transition, properties of the bitcoin network, and the role of bitcoin mining operations in the global energy production and consumption. Although the adoption path for bitcoin is likely to be volatile with an uncertain outcome, the opportunities offered by bitcoin mining in reduction of the greenhouse gas emissions and renewable energy transition are greater than generally assumed.

KEYWORDS: *renewable energy, greenhouse gas emission, grid balancing, electricity curtailment, gas flaring, bitcoin, decentralized money*

■ GREENHOUSE GAS EMISSIONS AND RENEWABLE ENERGY TRANSITION

Per capita energy production is a clear indicator of society's level of technological advancement and quality of life.[1] Access to affordable, reliable, and clean energy is rising globally[2] and is considered a basic human right in many countries. In parallel, efforts to reduce greenhouse gas emissions and reliance on fossil fuels in favor of renewable energy sources have been occupying the minds of activists, scientists, policy makers, and above all, common citizens. There are many ways how greenhouse gas emissions can be reduced. Researchers, organizations, and governments promote direct capture of greenhouse gases and renewable energy generation, which leads to an emergence of new industries.[3] Science and technology innovation, development, and commercialization increase the efficiency of energy production and consumption. Finally, measures adopted by all of us individually, such as limiting the use of plastics, switching off unnecessary lighting or heating, and using public transport, cycling, or walking, lead to significant energy savings.

Growing reliance on clean renewable energy sources, in particular, solar, wind, and hydropower, presents a clear path forward, despite their low penetration in the total energy production. The percentage of renewables in the primary energy mix has been rising slowly but steadily for several decades from 2.4% in 1990 to 5.7% in 2021 when the consumption surpassed 9000 TWh/yr, as shown in Figure 1a and b.[4] Solar and wind are considered to be the cleanest energy sources. Hydropower has been criticized for emitting methane, a greenhouse gas originating from organic matter decomposition, the extent of which varies greatly depending on climate and altitude.[5,6] Nuclear energy is considered neither renewable nor fossil based, has low greenhouse gas emissions, and is the most reliable energy source outside of gas, coal, and oil. However, it depends on a complex industry, with implementation and maintenance challenging due to high capital cost, lengthy (de)commissioning process, and nuclear waste storage.[7]

Wherever you stand on the climate change issues and urgency to act upon them, renewable energy solutions, which are environmentally friendly, ethically sound, and economically feasible throughout their entire lifetime cycles, are the natural step forward in the technological evolution of humanity. The penetration of renewables in the electricity mix has been much faster than in the primary energy mix, as shown in Figure 1c and d. Renewable electricity accounted for 28% of the total electricity production in 2021, compared to 20% a decade earlier, with solar and wind alone increasing 16 and 4 times, respectively.[8] Such a rapid growth brings new challenges. Both solar and wind are intermittent with unpredictable power output on an hourly/daily/weekly basis. Hydropower is reliable in the short term but has a significant seasonal variability. These variations lead to large swings in the power output, which disrupt the delicate supply and demand balance of the electricity grid.

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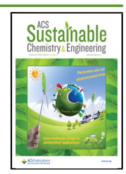

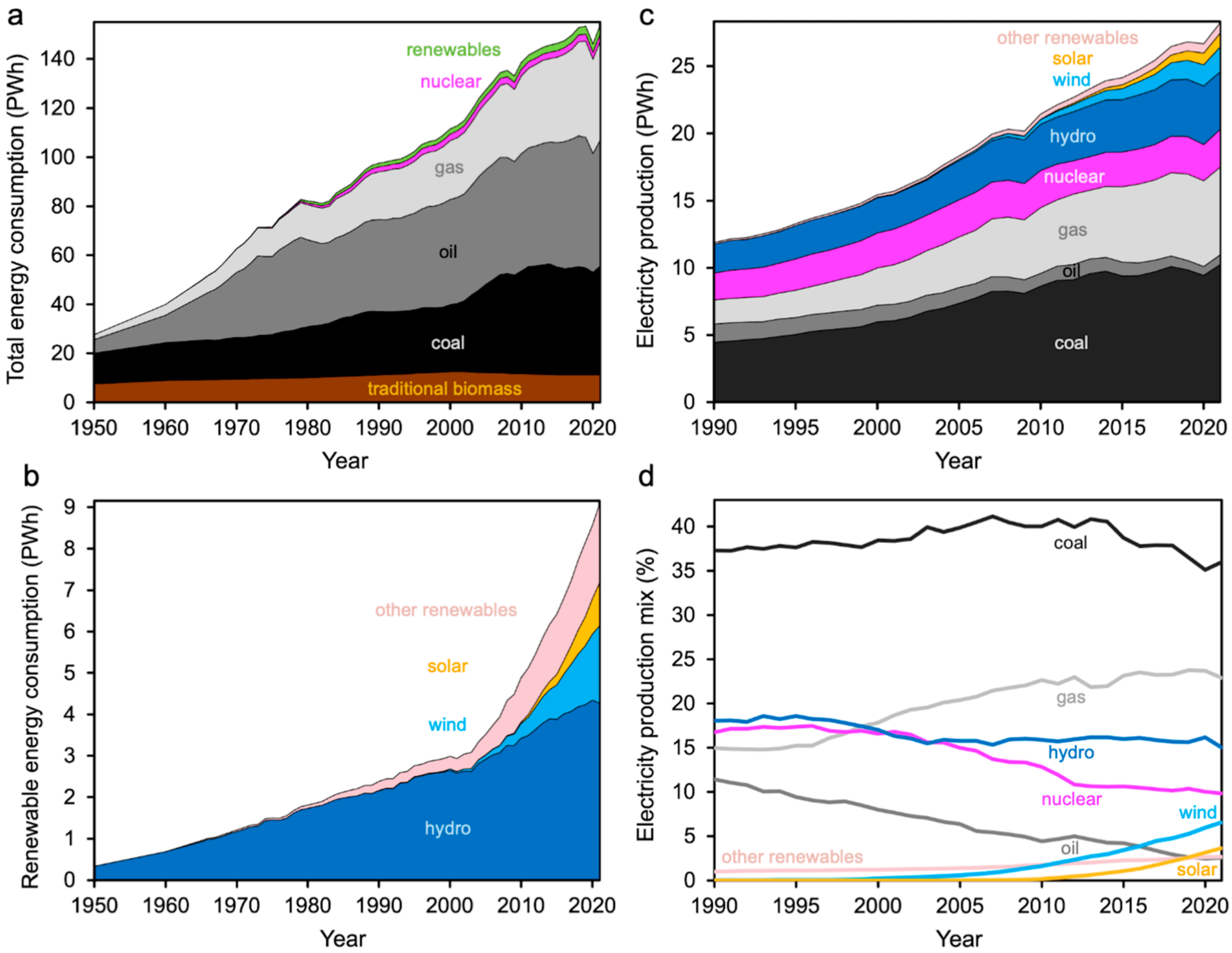

Figure 1. Global direct primary energy consumption and electricity production. (a) Annualized total energy consumption including fossil fuel sources, nuclear power, and all renewables combined.[4] (b) Annualized renewable energy consumption including hydropower, wind power, solar power, and other renewables (geothermal, biomass, biofuels, etc.).[4] The data in panels a and b do not take into account the inefficiencies in fossil fuel production. (c) Annualized electricity production by source.[8] (d) Electricity production mix demonstrating the exponential rise of solar and wind.[8]

Balancing the grid becomes more costly as the percentage of renewables rises, leading to undesirable phenomena, such as transmission congestion, electricity curtailment, and increased reserve capacity.[9] The short-term electricity overproduction can be partly mitigated by conversion to potential energy (hydro-pumped storage), chemical energy (batteries, hydrogen generation), or heat (aluminum smelters). Alternatively, the power output has to be curtailed, which represents a missed opportunity to generate electricity and increase return-on-investment of a power plant. There is a clear need for a flexible, fast-response electricity consumer, who is able to absorb excess electricity produced in off-peak times, and conversely, to reduce or pause consumption in times of high demand. With this in mind, we evaluate the role of bitcoin, a global electronic payment network that uses a significant amount of electricity, in transition toward renewable energy.

WHAT IS BITCOIN?

Bitcoin is a decentralized network, which uses asymmetric cryptography and a proof-of-work mechanism to verify and record transactions of eponymous currency (BTC) on a blockchain ledger without a trusted third party. A white paper outlining the principles of bitcoin was published by Nakamoto in late 2008,[10] and the network was launched by mining the first block in early 2009. Bitcoin relies on a proof-of-work consensus algorithm, which prevents network users from double spending and altering the blockchain history. The transactions are broadcasted and verified by asymmetric cryptography, which uses a public key to identify the transaction output and a private key to approve the transaction. The blockchain history is verified and recorded by over 10,000 independent nodes globally, some of which actively contribute to creating new blocks of transactions: these are called miners. The system assumes that the network participants inherently distrust each other and instead rely on the consensus algorithm to agree on the outcome. There are no other third parties who would take fees, censor transactions, or alter the ledger. Transactions are validated and secured by the bitcoin miners, who compete with each other to add new blocks and receive a reward for it.

Bitcoin was designed as a peer-to-peer electronic payment network. It was also borne out of the global financial crisis of 2007−2008, which is reflected in its monetary policy. The issuance of new BTC is implemented in the bitcoin code as a reward for mining a new block, starting at 50 BTC in 2009 and programmed to halve every 210,000 blocks (~4 years), with the current block reward being 6.25 BTC. One BTC is further denominated into 10^8 smaller units, called satoshi. These rules limit the total supply to 21 million when the last BTC is mined in 2140.[11] The built-in inflation rate of the total BTC supply (currently 1.7%/year), which diminishes predictably with time,

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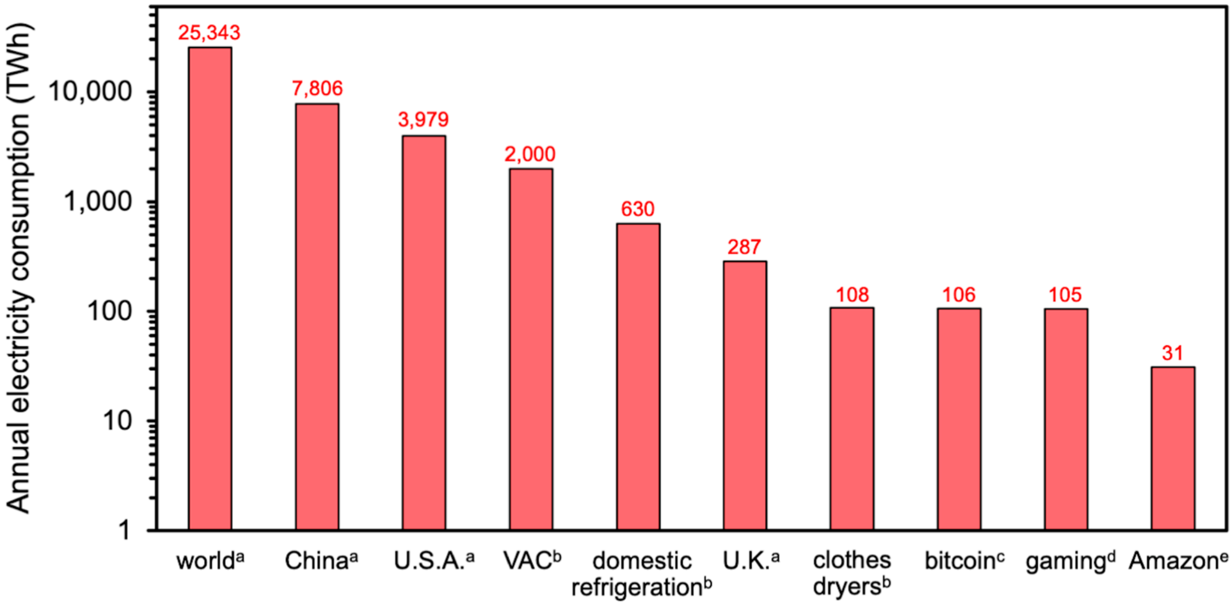

Figure 2. Annual global electricity consumption for different regions, sectors, and technologies on a logarithmic scale. Compiled from refs 35 (a), 12 (b), 34 (c), 37 (d), and 38 (e). VAC stands for ventilation and air conditioning.

could have been a response to the increasingly looser monetary policies of the major central banks. Anyone can propose alterations in the bitcoin code, should it be block resizing, monetary changes, or new features, through a *Bitcoin Improvement Proposal*, which is a process that must be supported by a vast majority of the miners to be implemented.

Bitcoin was originally designed as an electronic payment system based on sound money. However, its role appears to evolve with time and depend on its users.[12] For example, an investor in the U.S.A. or Europe might see bitcoin as a high-risk/high-reward alternative to more traditional investments such as bonds or equities. For citizens of countries, whose national currencies inflate at crippling rates or hyperinflate out of control (e.g., Turkey, Argentina, or Venezuela) and who have difficulty getting hold of other major currencies, bitcoin offers an opportunity to convert their earnings and savings into an asset with a guaranteed diminishing inflation rate. Finally, for a person anywhere in the world, who is unbanked (24% of global population),[13] has their access to the banking system restricted, suspended, or revoked, or relies on expensive remittance services such as Western Union or PayPal, bitcoin is an option to participate in a global permissionless payment network, resistant to state censorship. A special category of network participants, with a different set of incentives, are bitcoin miners, whose activity plays a role in the global electricity production and consumption.

CRITICISM OF BITCOIN

A widespread criticism of bitcoin has emerged over its 14-year history, some petty or unfounded, other highly relevant.[14−16] The bitcoin network is criticized for slow transaction speed (~2−4 transactions per second)[17,18] in comparison to the established digital payments systems such as Visa and Mastercard (~4000−7000 transactions per second).[19] This unearths an important question: if bitcoin is so much less efficient than existing payment technology, why do we need it? The answer lies in decentralization, security, and settlement finality of the bitcoin network. The more decentralized the payment verification is, the more inefficient the transactions are, due to the proof-of-work principle and redundant blockchain copies stored at numerous verification nodes around the globe. Visa and Mastercard are trusted third-party processors mediating payments between different entities, and their fast network speeds are only possible thanks to their centralization. This works well if one trusts these intermediaries not to mismanage their records, recognizes they can be hacked, accepts transaction censorship and reversibility, and is willing to pay the transaction fee. In order to scale up its transactions throughput, bitcoin would have to become more centralized and therefore less secure, an issue known as the *blockchain trilemma*.[20] In fact, the bitcoin scalability issue led to the *block-size war* of 2015−2017, in which proposals of increasing the block size to facilitate faster transactions were zealously discussed.[21] The long dispute resulted in splitting the bitcoin network via a mechanism called *hard fork* into two separate blockchains with identical histories but divergent futures: *bitcoin* (maintaining the original maximum block size of 1 MB) and *bitcoin cash* (adjustable block-size cap, now 32 MB). The fact that the majority of software developers continued working on the original bitcoin blockchain and bitcoin's market capitalization continued to increase indicates that keeping the block size small is the way forward. Resistance to increase the bitcoin network throughput at the expense of its decentralization, security, and hard monetary cap demonstrates the evolution of bitcoin from the original role as a peer-to-peer electronic cash toward a digital store of value.

Often criticized are the high transaction fees, currently around 1 USD per transaction, which can, nevertheless, reach up to 50 USD during peak times,[17,22] making low-value transactions cost ineffective. This is being addressed by development of decentralized *layer 2* (bitcoin being *layer 1*) solutions such as the *Lighting Network*, a rapidly growing payment protocol, which allows near-instant low-value payments at a cost of reduced security.[23] In contrast, transferring large amounts of bitcoin is highly efficient; one can reach final settlement within half an hour at off-peak times,[24] without any cap on the transferred amount.

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Criminal activities committed using bitcoin and other cryptocurrencies, e.g., money laundering, illegal drugs, or funding terrorism, are often pointed out.[25] Since bitcoin relies on a publicly distributed blockchain ledger, the transactions are pseudonymous, not anonymous. Therefore, once a real identity of a transacting party is identified, their whole transaction history can be traced back using their public key(s).[26] In fact, the blockchain record has successfully been utilized by law enforcement to identify and prosecute illegal activities.[27] While there is evidence that crime moves increasingly more online, criminal activity constitutes only a marginal fraction of the total cryptocurrency transaction volume, which has decreased notably in the past few years (0.15% in 2021).[28,29] Meanwhile, one of the most commonly used anonymous methods of illegal payments is fiat cash.[30] The Russian invasion of Ukraine in 2022 has demonstrated that bitcoin and other cryptocurrencies are neutral, apolitical, censorship-resistant tools, which enable transactions serving quite opposite purposes, i.e., financial aid for the Ukrainians as well as sanction circumvention for the Russians.[31] Truth remains that the rapid rise of the bitcoin market cap instigated an emergence of fraud, scams, and hacks.[32] The most recent and painful example of all is the November 2022 collapse of FTX, the third largest cryptocurrency exchange. FTX appeared to be a booming business backed by prominent institutional investors and celebrities just days before a fatal solvency crisis triggered by mass client withdrawals. The cause of the collapse and subsequent bankruptcy of FTX appears to be misappropriation of customer funds, using which a highly leveraged trading side business was fueled, leading to estimated losses of over $8 billion.[33] Such events appear to be an unpleasant reality of any emerging, speculative, and unregulated market.

One of the most legitimate concerns is the growing energy consumption of the bitcoin network.[11] Depending on the current bitcoin value and mining difficulty, the entire network currently consumes around 80−140 TWh of electricity annually,[34] which is comparable to an entire country such as Pakistan (132 TWh/yr), Netherlands (113 TWh/yr), or Colombia (76 TWh/yr) and constitutes 0.4% of global electricity consumption and 0.1% of global primary energy consumption.[35,36] However, it is more appropriate to make a comparison to other electricity consumption globally, for example, domestic refrigeration (630 TWh/yr), clothes dryers (108 TWh/yr), or video gaming (105 TWh/yr).[12,37] A comparison of electricity consumption for selected regions, sectors, and technologies is shown in Figure 2. We leave it for the reader to judge whether the existence of a global decentralized payment network based on an uncensored digital commodity is justified alongside other electricity uses. Importantly, the proof-of-work mechanism ensures that real-world resources have been spent to create new BTC and that it cannot be debased the same way fiat currencies easily can. One could therefore expect that the long-term average of bitcoin's market capitalization should, at the very least, be comparable to the cost of electricity spent to mine it, provided the bitcoin network remains active.

BITCOIN MINING

The bitcoin network uses the asymmetric cryptographic hash function SHA-256 to generate new blocks of transactions. The hash function converts a variable-sized data input to a fixed-sized data output—a number called *hash*, which can be thought of as the fingerprint of the new block. The input (new block's transactions, hash of the previous block, and so-called *nonce*) is hashed to produce the new block's hash.[10] Miners have a simple but computationally demanding task: to find the nonce (a number used once) by guessing from billions of possibilities. But how do they know what nonce to look for? The consensus algorithm requires the hash to start with zeros, the number of which is determined by the proof-of-work difficulty. Once the nonce is first found and broadcasted, it requires minimal effort for other nodes to validate it as true, and the new block, connected to the previous one by containing its hash, is added to the blockchain. The maximum block size allowed by the protocol is 1 MB, and the size of the entire blockchain history is ∼450 GB as of January 2023.[39] In order to maintain the prescribed average block verification time of 10 min, the mining difficulty is adjusted periodically in response to changes in the mining efficiency and number of active miners. The protocol evaluates the average verification time after 2016 blocks (∼14 days) and adjusts the proof-of-work difficulty by increasing (harder) or decreasing (easier) the required number of the leading zeros in the hash.

The electricity spent to find the nonce is the winning miner's real-world proof-of-work, for which he/she is rewarded with a newly issued BTC and transaction fees. The electricity burned during block verification safeguards the security the network, which is proportional to the number of hashes performed per unit of time, the so-called *hash rate*, currently sitting near its all-time-high at 160−300 exahashes per second.[40] Since SHA-256 is a one-way, asymmetric hash function, it is practically unfeasible to revert it and calculate the nonce from a known hash. If a bad actor wanted to change information somewhere in the blockchain history, they would have to rehash all the subsequent blocks, which has been shown to be exponentially less probable and costly with an increasing number of blocks.[10] In this system, cheating is possible but significantly more expensive than playing by the rules.

Bitcoin mining hardware has come a long way since 2009.[41] Initially, it was possible to mine bitcoin using central processing units. As the hash rate increased with early adoption of bitcoin, multicore graphics processing units were better suited for the job. Once the hash rate had reached a petahash per second, it became increasingly more profitable to employ the efficient application-specific integrated circuit (ASIC) miners, manufactured specifically to solve the proof-of-work algorithm.[11] Alongside the continuous increase in mining hardware efficiency,[12] mining pools of large numbers of individual units connected from anywhere in the world have been introduced to utilize their collective computational power. BTC mined by the entire pool is distributed proportionally to the relative contribution to the combined hash rate, thus guaranteeing predictable rewards for individual and less powerful mining units. Next, we discuss the surprising consequences of bitcoin mining, which go beyond the simplistic "the more energy bitcoin uses, the worse for the environment it is" view.

Profitability of bitcoin mining is primarily determined by the hardware efficiency, electricity cost, and mining site climate. Miners are likely to adopt one of several approaches when looking to set up their operations: (1) seek reliable and grid-connected electricity sources of moderately priced electricity and a guaranteed 24/7 power output, (2) seek reliable but stranded sources with substantially discounted prices, requiring capital investment, or (3) seek intermittent sources at substantially discounted or even negative rates, requiring operational flexibility. Cooling the ASICs, much of whose electricity input is converted to heat, represents an additional

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operational cost. Hence, setting up mining in different climates will have different economic implications. For example, access to cheap and clean hydroelectric power in a cold environment of an abandoned Norwegian olivine mine with an abundant water source for the ASICs cooling offers significantly discounted operating conditions for the miners.[42] Political stability and regulatory clarity are also important. A complete ban of cryptocurrency mining and trading in China in 2021, which drove the majority of miners away, hurt the bitcoin network initially by reducing its hash rate (and therefore security) by two-thirds.[40,43] However, it also demonstrated miners' willingness to quickly relocate to countries with more favorable conditions, which reduced the hash rate percentage in China from 40%–75% preban to 20% postban and thus increased network decentralization.[44]

■ BITCOIN IN GREENHOUSE GAS EMISSIONS AND RENEWABLE ENERGY

The current electricity mix of bitcoin is difficult to evaluate due to the decentralized nature of mining and the lack of reliable data on what electricity sources individual miners utilize. It evolves dynamically in time and varies on geography, politics, and electricity prices. We have therefore estimated the bitcoin electricity mix from the distribution of the bitcoin hash rate in different regions and the corresponding electricity mix in these regions (Figure 3). Specifically, the bitcoin hash rate for a given electricity source (HR_S) is calculated as a sum of the bitcoin hash rates in different countries (HR_C), weighted by the fraction of the given electricity source in those countries (f_S):

$$HR_S(\%) = \sum_C f_S \cdot HR_C(\%) \tag{1}$$

Equation 1 is simplistic as it does not reflect the miners' operating conditions and preferences in individual countries. Our analysis could be overly conservative for countries with excess renewable energy or overly optimistic for countries where miners are incentivized to utilize fossil fuels. It also does not capture miners hiding behind virtual private networks of other countries. Nevertheless, it provides a crude insight into the current state of bitcoin mining and identifies a research opportunity to assess its current electricity mix and its future evolution. Our analysis in Figure 3 shows that while the fossil fuels' share of the hash rate has gradually been declining since 2019, the difference is being made up by the nuclear power, while the renewables' share remained unchanged (25%). This has undoubtedly been driven by the decrease of the hash rate in China (60% coal, 5% nuclear) balanced by the increase of the hash rate in the U.S.A. and Canada (5%–20% coal, 15%–20% nuclear). The constant renewables' share of the hash rate is understandable given the marginal increase (4%) of renewables in the global electricity mix since 2019. The truth remains that, despite our approximate analysis, a significant portion of bitcoin (63%) is likely being mined using fossil fuels.

In June 2022, the gas-fired Greenidge power plant, at Seneca Lake, N.Y., U.S.A., was denied a permit renewal to operate since the significant fraction (up to 55%) of its power output has been used for behind-the-meter bitcoin mining.[45,46] Naturally, exploitation of fossil fuels to power bitcoin mining is questionable and experiences regulatory pressure. Originally a coal-fired facility, Greenidge was recommissioned in 2017 as a natural gas power plant and since 2020 utilized bitcoin mining to monetize off-peak periods, during which they struggled to sell electricity to the grid at a profit. Behind-the-meter bitcoin mining used to moderate electricity output locally at the power station appears to be an excellent grid balancing tool. However, recommissioning of the fossil fuel facilities to power bitcoin mining exclusively, which appears to be on the rise in North America, is not a desirable trend.[47]

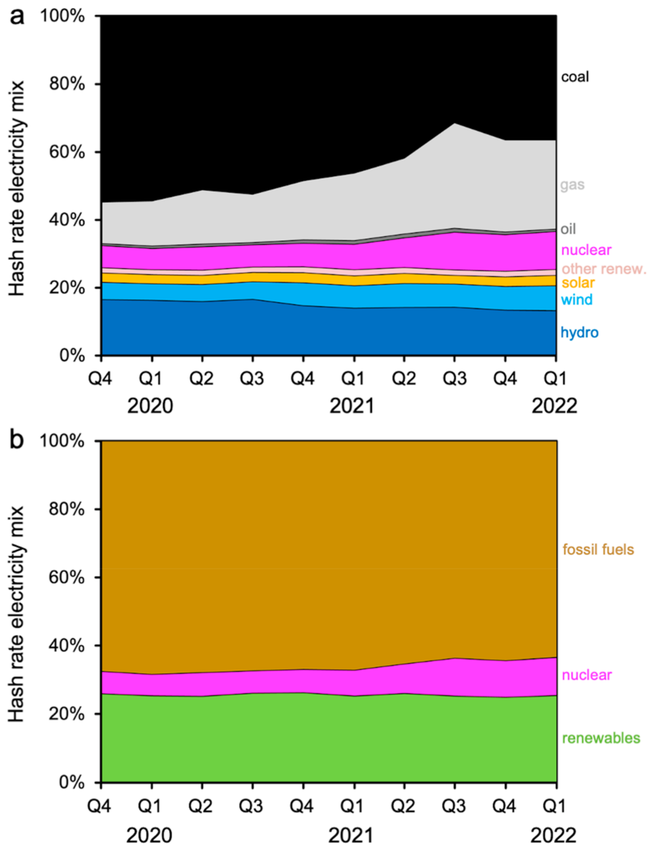

Figure 3. Estimated electricity mix of the global bitcoin hash rate since late 2019. (a) Hash rate electricity mix for all recorded sources: coal, gas, oil, nuclear, hydro, wind, solar, and other renewables. (b) Hash rate electricity mix for all fossil fuels, nuclear power, and all renewables. This data set was determined using eq 1, from the hash rate distribution in countries with significant mining operations (U.S.A., China, Kazakhstan, Canada, Russia, and few others)[44] and the electricity mix of these countries.[8]

Access to cheap electricity is a necessity for miners to remain operational. They are motivated to avoid the high-demand and therefore high-cost electricity sources located in heavily urbanized areas. Instead, they should tend to scoop up inexpensive electricity from excess production, stranded sources, or areas with high transmission losses, which are not in direct competition with domestic and industrial use. Miners act as "buyers of last resort" in this case, favoring nonrival energy, consumption of which does not reduce supply nor increase prices for other consumers.[48] Analysis of bitcoin mining in the U.S.A indeed showed that states with high penetration of renewables and low electricity prices offer the best economic incentives for miners and initiatives for carbon capture.[49]

The increasing need of balancing the electricity production and consumption is one of the biggest challenges of the renewable energy transition. The electrical grid has to operate in a constant balance between the supply and demand to maintain its utility frequency, which is more challenging to achieve with an increasing percentage of intermittent renewable sources. Grid balancing requires measures such as demand response, trans-

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mission expansion, peaker plants, or energy storage, all of which increase electricity prices. So, are there other ways to minimize the power output fluctuations in a more economically viable way? Power-hungry but temporally flexible operations can serve as highly efficient "battery-like" systems for the grid, preventing excess electricity to be wasted.[50] Bitcoin mining and operations of the likes of Amazon Web Services, Google, or Netflix fit the bill. An analysis of the integrated energy system combining a renewable source power plant and a computational data center has demonstrated that such an approach offers higher net present value than the standalone power plant solution.[51] However, the main difference between a conventional data center and bitcoin is the feasible interruptibility of the latter. Similar conclusions were reached for specific analyses of wind power in Brazil[52] and both wind and solar power in Texas.[53] The Texas grid operator, ERCOT, had realized this opportunity and began to work with bitcoin miners to incorporate them as a controllable load resource on the grid.[54] Such synergy could accelerate adoption of renewable energy solutions, reducing the number of operations facing economic difficulties.

The peak and trough nature of the renewables exacerbates a historically marginal mechanism on the grid: electricity curtailment.[55] Through curtailment, the electricity output (for example, solar mid-day and wind at night) is cut back in order to balance the supply and demand. Opportunities for bitcoin mining are enormous because the amount of curtailed electricity is not negligible and will only increase with deeper penetration of renewables. For example, in 2020, Texas and California curtailed 4.9 and 1.5 TWh of renewable electricity, respectively, which could have been generated with near-zero carbon emissions to mine 9% of all BTC issued that year (42,000 BTC equivalent to $470 million).[34,53,56] Another example is the preban history of bitcoin mining in China, during which the miners demonstrated remarkable seasonal mobility, exploiting huge excess in the hydropower output during the wet summer months.[12,44]

The fraction of curtailed electricity is likely to be the highest in the "greenest" (highest renewables penetration) and "poorest" (inefficient or isolated grids) regions, disincentivizing adoption of renewables and infrastructure development in impoverished countries. Bitcoin miners can mitigate curtailment by providing a stable, predictable load connected to a grid, which can be dialed down or turned off during peak times.[57] This power release would mimic conventional peaker plants, which generate additional electricity during high demand. Bitcoin mining therefore provides a flexible, interruptible electrical power sink, with a rapid on/off response to smooth out the power output peaks and troughs, akin to other alternatives, such as hydro-pumped storage, aluminum smelters, or electrolytic hydrogen production.[58−60] All in all, strong incentives supported by robust analyses suggest that the excess electricity from renewables can be turned into profit using bitcoin mining, which in turn might have a future as a supply−demand balancing tool for the grid. Only the future will tell whether the miners are incentivized to participate in such developments and which energy sectors are willing to implement them at a large scale.

Several niche applications of bitcoin mining are worth discussing. Gas flaring is one of them. It taps into stranded natural gas, located in deposits far from any pipeline infrastructure, which is normally burned or, even worse, released straight into the atmosphere.[61] The heat generated by the gas burning is converted to electricity using small turbines with a few MW power output, which is then used to mine bitcoin. The principal component of natural gas is methane, which is a significantly more potent greenhouse gas than CO_2. Therefore, flaring, as opposed to direct release into the atmosphere, reduces the resulting warming effect from 6 to 16 times, depending on the time scale.[62] Crusoe Energy is an example of a company leading these operations, which, although in their infancy, attract well-established oil and gas production giants such as Exxon Mobile and ConocoPhillips in Northern America and the Middle East.[63] On the one hand, this approach is a mere CO_2-emitting monetization of the gas flaring. There is a risk that new gas wells, which need not to be flared or utilized for other reasons, are drilled solely to power bitcoin mining. On the other hand, this strategy presents a significant opportunity for mitigation of existing greenhouse gas emissions.

Utilization of energy released from methane generated in landfills is another promising use case. Many landfill operators are required to burn off methane generated by the decomposition of the waste in order to reduce greenhouse gas emissions, at an additional cost of building and operating the gas burning facility. Vespene Energy is a company planning to turn this liability into an asset. They offer to convert the generated heat to electricity using 1.5 MW turbines, use it to power bitcoin mining, and share the profits with the landfill operators.[64]

Ocean thermal energy conversion (OTEC) is also being considered for bitcoin mining.[65] OTEC exploits the temperature gradient between the warm surface seawater and cooler deep water, converting heat to mechanical energy and to electricity. Additionally, OTEC is considered to be utilized for mining of polymetallic nodules found on the ocean floor, predominantly in the Pacific.[66] Although first realized in 1930, only two isolated implementations of OTEC exist today, in Hawaii and Japan. The pilot OTEC plants will be stranded electricity sources with enormous capital cost and investment risk prior to scaling up. The reduction of the construction and operation costs by utilizing the generated electricity to make profit from bitcoin mining and the accessibility of cheap seawater cooling for the ASICs make this approach attractive.

Although these alternatives currently play only a marginal role in energy production and bitcoin mining, their potential is not marginal at all. The amount of flared gas in 2020 is estimated to be equivalent of 49 GW of electricity globally.[12] There are roughly 1250 landfills in the U.S.A. alone, which, if harnessed, would amount to roughly 2 GW of power.[67] Potential power output for global OTEC implementation is estimated to be 2−7 TW,[68] on par with the global electricity consumption today (2.7 TW).[35] These schemes are speculative and their outcome uncertain. But that is the exact reason why bitcoin is relevant here. Co-implementing bitcoin with these economically risky operations can bridge the dreaded "innovation valley of death", shown schematically in Figure 4, which all innovations face along their adoption path. Bitcoin miners would act as "buyers of first resort" in this case, pioneering the exploitation of energy sources in underdeveloped regions before investments into grid infrastructure are made and the demand for electricity catches up with the supply.[69]

Finally, recognizing that future predictions of a complex system are dubious even with the best of models, let us consider future bitcoin electricity consumption. It has been estimated to peak between 80 and 700 TWh/yr between 2024 and 2027, generally trending down thereafter with further fluctuations, driven by the bitcoin price and halving of the block reward.[12] The long-term average is expected to stabilize anywhere between 0 (BTC becomes worthless) and 300 TWh/yr (BTC market cap reaches $10 trillion), as price volatility and the effect

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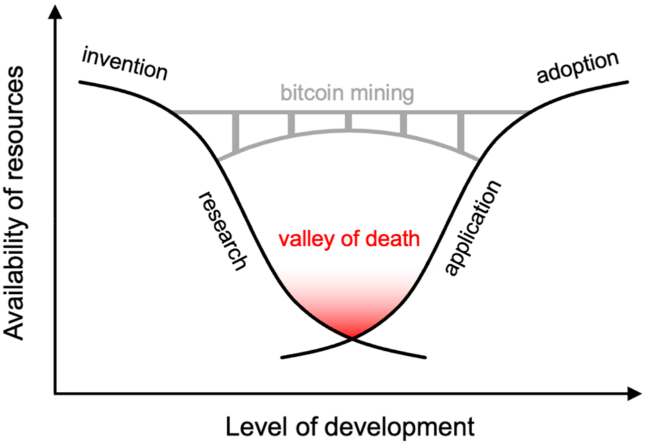

Figure 4. Innovation valley of death for the development and implementation of novel renewable energy technologies, which could potentially be bridged by bitcoin mining. Inspired by ref 65.

of halving decrease. Importantly, bitcoin market capitalization is unlikely to continue growing at the recent fast rates due its increasingly larger size, thus leading to a slower increase of its electricity consumption.

OTHER CRYPTOCURRENCIES

Other cryptocurrencies have been developed based on various consensus algorithms, monetary policies, and use cases. These altcoins (alternative cryptocurrencies) range from layer 1 protocols (litecoin, ethereum, cardano) to layer 2 tokens (issued on layer 1 protocols), stablecoins (pegged to a fiat currency), and central bank digital currencies (programmable monies issued by central banks). Cryptocurrencies represent a nascent technology at an early development stage, involving experimentation, speculation, and risk, analogous to the 1990s dot-com boom. The vast majority of the >20,000 altcoins are technological dead-ends, unsecure projects, or outright Ponzi schemes. The intentionally unhurried development of the bitcoin protocol makes it less attractive for software developers keen to implement blockchain technology in applications ranging from decentralized finance, smart contracts, and supply chain to digital art, which they instead seek to realize in other projects.

Some cryptocurrencies use the proof-of-work consensus algorithm discussed above. The second largest cryptocurrency by market cap, ethereum, which has been successful in attracting decentralized applications development on top of its layer 1, has recently migrated from proof-of-work to proof-of-stake. In a proof-of-stake system miners become validators, who are required to stake minimum 32 ethers, the network native currency, in order to validate the network transactions and earn rewards. Crucially, the validators no longer compete to confirm the blocks at the same time, and instead, one validator is randomly selected to solve the computational task and to validate the new block. This decreases the electricity consumption to less than 0.1% at the expense of lowered security and leads to larger centralization of the network based on access to capital. Other relevant consensus algorithms include proof-of-weight, proof-of-burn, or proof-of-activity.[70]

The protocol malleability and rapid development of non-bitcoin cryptocurrencies also are their biggest weaknesses. Particularly problematic are the active connections to the founding teams (risk of centralization, attacks, lobbying), unpredictable monetary policy (elastic money supply, transaction reversals), and undemocratic distribution of the coins (early venture capital investment, premining). The U.S. Securities and Exchanges Commission's ongoing view is that apart from bitcoin and possibly ethereum, most other altcoins are or will be classified as unregistered securities.[71] This might be a weak spot for many crypto projects, blockchain developers, and exchanges, who will have to alter their activities in order to comply with regulations. In contrast, development of the bitcoin protocol proceeds in a decentralized manner, with no central operation to be raided in order to arrest the bitcoin CEO, force a change in the protocol, or shut all the network servers down. For these reasons, bitcoin (so far) remains the largest cryptocurrency by market capitalization, network effect, and blockchain security.

FUTURE OPPORTUNITIES AND CHALLENGES

Bitcoin is a unique combination of a financial asset and energy commodity. That is, it allows transfer of energy, stored within it during the proof-of-work mining process, across the globe without a limit. Whether to send value from Switzerland to Argentina without intermediaries or to convert energy from a stranded source in North America to purchase grid electricity in Japan, people find utility using it. It is hard to predict what path bitcoin will take and what role it will play in global energy. Its adoption will likely increase within the next decade, but it will remain speculative and volatile. Beyond that, its fate depends on what status will the major world economies allow it to attain. At the very least, it may remain an effective payment tool in the developing countries with inefficient or restrictive financial services.

To counteract critics skeptical about the role of bitcoin in renewable energy transition,[72,73] we have summarized those aspects deserving a closer inspection by the energy industry, policy makers, and general public. It may be beneficial to incentivize bitcoin mining in a way, which will facilitate grid balancing, curb electricity curtailment, and accelerate penetration of renewables. Regulation of mining profits through carbon emission-weighted subsidy of renewable energy industries has been proposed.[74] This would be beneficial if introduced sensibly after a robust discussion among all parties involved. However, it is unclear how it can be coordinated across many jurisdictions with differing electricity mixes, to avoid the game theory-driven evasion of the regulations by the miners in search for the most profitable operations.

If the rise of bitcoin in the coming decade facilitates, coincides with, and thrives on adoption of renewables, and predictions about its electricity consumption declining thereafter are broadly correct, increasingly more renewable power will become available for the grid. A particularly appealing pathway for bitcoin adoption is the bottom-up integration of miners alongside domestic solar power and battery energy storage.[75] This model embraces the decentralized nature of bitcoin, maximizes electricity utilization, and minimizes power transmission losses. Bitcoin's appetite for stranded energy sources in cold, remote places, away from urban areas will reduce the social cost of increasing electricity prices for other consumers. Co-location of bitcoin mining with pilot plants can accelerate innovation and adoption of new renewable technologies. Allowing bitcoin mining to prove itself in this endeavor seems a more rational approach than heavy regulations we have seen imposed recently in some jurisdictions.

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Bitcoin will face risks and challenges. There are regulations such as total bans, government expropriation, excessive taxation, or severance from the banking system. The bitcoin network requires electricity and the Internet for its operation; however, the world would be facing a whole set of other issues if these modern necessities were unavailable. Electronic waste is another well-recognized problem. As the obsolete ASICs are replaced by more efficient models, they become electronic waste with no other use.[72] An optimistic expectation would be that as Moore's law is starting to reach its physical limits and bitcoin's market cap stabilizes, the lifetime of the ASICs lengthens. Furthermore, older ASIC miners can be recommissioned if the hash rate or electricity prices decrease.

In conclusion, examining various incentives for bitcoin mining reveals the unexpected role it may play in the greenhouse gas emission reduction and renewable energy transition. We believe that bitcoin does not deserve to be casually written off as a waste of electricity, which is usually done under the assumption that it has no utility at all. Instead, it represents an ingenious piece of technology, which converts a real-world energy into an immutable blockchain ledger of transactions, with BTC as both the transaction medium and the incentive for securing the bitcoin network. One question left for everyone to ponder is this: is the world a better place with or without bitcoin in it?

■ ASSOCIATED CONTENT

Data Availability Statement

The data and analyses underlying this work are openly available in HeyRACK repository at https://www.doi.org/10.48700/datst.6vwae-zsb30.

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Notes

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