Can Bitcoin Stop Climate Change? Proof of Work, Energy Consumption and Carbon Footprint (SoK)

Juan Ignacio Ibañez[1,2], Alexander Freier[1,2,3]
[1]Centre for Blockchain Technologies, University College London, London, UK
[2]Facultad de Ciencia Política y Relaciones Internacionales, Universidad Católica de Córdoba, Córdoba, Argentina
[3]Energiequelle GmbH, Feldheim, Germany
j.ibanez@ucl.ac.uk, freier@energiequelle.de

***Abstract*—Despite their potential in many respects, blockchain and distributed ledger technology (DLT) technology have been the target of criticism for the energy intensity of the proof-of-work (PoW) consensus algorithm in general and of Bitcoin mining in particular. However, mining is also believed to have the potential to drive net decarbonization and renewable penetration in the energy grid by providing ancillary and other services. In this paper, we systematize the state of the art in this regard. Although not completely absent from the literature, the extent to which flexible load response through PoW mining may support grid decarbonization remains insufficiently studied and hence contested. We approach this research gap by systematizing both the strengths and the limitations of mining to provide flexible load response services for energy grids. We find that a net-decarbonizing effect led by renewable-based mining is indeed plausible.**

***Index Terms*—Blockchain, Environmental Impact, Decarbonization, Ancillary Services, Flexible Load Response, Sustainability, Renewable Energy Sources.**

I. Introduction

A. Bitcoin, proof of work and energy consumption

In 2008, Satoshi Nakamoto [1] published the Bitcoin whitepaper. This paper introduced a peer-to-peer payment system based on a particular configuration of Distributed Ledger Technology (DLT) in the form of an append-only data structure known as a chain of blocks or blockchain. The core innovation of this system resided in *Nakamoto consensus*: combining the blockchain with Dwork and Naor's [2] proof of work (PoW) to support a decentralized, censorship-resistant means of payment.

The design was very successful and resulted in the emergence of the Bitcoin protocol,[1] and the meteoric rise of its native token, "bitcoin," as the world's first and most important cryptocurrency. In recent years, Bitcoin's market capitalization even reached a trillion US dollars [3], [4].

Nonetheless, cryptocurrencies in general and Bitcoin in particular have been subjected to increasing public scrutiny in recent times, there being a debate of whether these digital assets possess a "social license to operate" [5, p. 3]. In particular, cryptocurrencies are being questioned for the energy intensity of the PoW mechanism, which is believed to lead to very significant greenhouse gas (GHG) emissions (see II).

The PoW mechanism enables decentralized systems to achieve consensus in a manner that is resistant to Sybil attacks, i.e. preventing the nigh-costless creation of numerous digital identities to unduly influence the network [6]–[10]. This is managed by awarding the right to append a new block to the chain (which also entails a bitcoin subsidy known as "block reward" and the possibility of requesting transaction fees to include transactions in one's block) to the node that has found a unique number called "nonce." This process is known as "mining." Because the nonce can only be found by randomly guessing through the energy-intensive operation known as hashing, the probability of successfully mining a bitcoin is (for similar hardware) proportional to the energy spent in mining. As a result, digital identities are no longer costless, but costly, as they are tied to a scarce resource (energy) [3], [9], [10].

This design has proven so far to be solid. To date, Bitcoin is the most successful, widely-adopted and battle-tested cryptocurrency [3], [4]. PoW in particular has proved to be very instrumental towards advancing its goals of censorship resistance and the stability of the protocol that makes it a promising store of value [3]. Nevertheless, this success has drawn criticism as well.

The rise in bitcoin's price has entailed a growing interest in holding bitcoin. As mining is one of the main ways in which bitcoin can be obtained, mining operations have also grown throughout the globe, with the corresponding increase in energy consumption. Bitcoin advocates see this as a positive development, with a higher hashrate entailing more security for the protocol [3]. However, critics highlight that this implies a significant carbon footprint,[2] and moreover a footprint that might continue to grow in the future if Bitcoin's adoption grows further.

B. Flexible load response through cryptocurrency mining

Bitcoin advocates argue not only that the energy consumption and carbon footprint of Bitcoin are overestimated (see II), but also that Bitcoin might even be in a position to provide an environmental *service*. That Bitcoin is energy-intensive and hence adds load to the energy grid is however acknowledged. In turn, the tenet is that this increase in the load may

[1]The Bitcoin protocol has been "forked" several times, from a common ancestor into multiple chains of which several make claims to be the "original" Bitcoin protocol. Where not indicated otherwise, "Bitcoin" in the remainder of this paper refers to the Bitcoin fork with the largest market cap to date: Bitcoin Core (BTC).

[2]Carbon footprint is directly proportional to hashrate (everything else constant) [11].

be *net decarbonizing*. This is because Bitcoin mining may provide flexible load response capabilities that would make the renewable energy business more profitable and, hence, enable its penetration.

In this regard, the state of the art is limited. Although many have sought to estimate Bitcoin's carbon footprint (see II),[3] only a limited number of papers have put their focus in bitcoin and flexible load response [13], [14]. The work is still in embryonic stages, highly contested and not systematized. This article seeks to fill this gap.

C. Our contribution

We provide an overview of the characteristics of both Bitcoin mining and the renewable energy sector, the potential complementarities, and their limitations. In doing so, we provide the first systematic review of this potential synergy in the hopes to stimulate both greater awareness and deeper research exploring this subject.

To do this, we conduct a comprehensive literature review of academic papers, industry reports, and divulgation articles, as well as interviews with specialists and market players (see IX-H).

We structure the paper in the following manner. First, we provide an overview of the literature on Bitcoin's environmental impact and, more generally, cryptocurrencies. Second, we discuss the renewable energy market and the main challenges to renewable energy penetration and decarbonization. Third, we present the specific characteristics that make PoW mining unique which could bear relevance to the renewable energy sector. Fourth, we explain how Bitcoin mining is applied or could be applied in different niches of the renewable energy sector. Fifth, we explicate the positive effects of supplementing the path to decarbonization with green Bitcoin mining. Sixth, we consider the different limitations of this approach and the challenges to be overcome. Seventh, we contrast Bitcoin mining with other activities that could potentially compete with Bitcoin mining in the role of the ancillary services provider. Finally, we conclude with a general discussion of our findings, their limitations and potential future work.

II. Bitcoin's environmental impact

A. Public discussion: context

Bitcoin's high energy consumption, even raised to Satoshi Nakamoto in 2010,[4] constitutes the main environmental objection to the digital asset. This has led to slower cryptocurrency market penetration and even subsequent spill-over effects on price volatility as a result [15]. In consequence, energy consumption has consistently emerged as the main focus of academic research on the matter [14].[5]

Bitcoin mining is conducted throughout the world, but displays distinct spatial distributions along a clear pattern [17]: in their search for cost-effective mining locations, miners strive to find the cheapest energy sources [11], [18]–[20].[6] These sources may be carbon-intensive, leading to environmental concerns[7] particularly in a context where the 1.5 degree temperature increase target is being strongly advocated for [24].

While some bitcoin mining is indeed powered by carbon-intensive energy sources, the extent to which this is the case is debated [25]. Furthermore, China's [3], [11], [19], [26] and Kazakhstan's [27] cryptocurrency bans consolidated[8] the pre-existing trend to mine bitcoin in the US.

B. Current carbon footprint estimations

The main question in the literature to date is how high Bitcoin's carbon footprint is. There is no question that Bitcoin's energy consumption is high compared to, e.g. proof-of-stake (PoS) systems [9], [28]–[32]. Nonetheless, there are disagreements about its actual magnitude and how to represent this magnitude without resorting to misleading comparisons or metrics.

a) Data sources: In the first regard, estimations vary significantly. According to the White House Office of Science and Technology Policy (OSTP) [28], Bitcoin's electricity consumption ranges between 72 and 185 billion kWh per year.

One of the most widely used scientific sources is the CCAF's (Cambridge Centre for Alternative Finance) CBECI (Cambridge Bitcoin Energy Consumption Index).[9] For GHG estimations, the CBECI assigns the carbon intensity of the grid mix that corresponds to mining pools' IP addresses, leading to the limitation of ignoring behind-the-meter renewable mining. In contrast, the Bitcoin Mining Council (BMC) prioritizes instead first-hand data from miners instead [33], which however entails its own limitations related to self-reporting and data comparability (see also the discussion of theories of causality below). Non-scientific sources are of course also often used in public discourse.[10]

b) Magnitudes, metrics and attribution: In the second regard, multiple magnitudes have been used to depict Bitcoin's

[3]Not so many of which did so in a scientific fashion [12].

[4]https://bitcointalk.org/index.php?topic=721.msg8114#msg8114

[5]However, in spite of numerous publications on the matter, the area may still be considered under-researched [12]. Coinshares [16], for instance, argues that only one recent report (other than its own) uses a methodology that is sufficiently granular and accurate, namely Carter and Stevens' [3].

[6]For a discussion of Bitcoin's special sensitivity to electricity prices, see IV.

[7]Cases such as Iran [20], Kazakhstan [11], [16], [21], parts of China,[3], [13], [16], Venezuela [21] and parts of the United States (US) and Canada [11], [16] (where outdated, inefficient natural gas power plants are retrofitted for bitcoin mining [13], although criticism is sometimes also levied when the energy source is green, as it is no longer available for other uses [22]) usually star these concerns.

Malfuzi et al [23] show that Iran, Russia and China are the best countries to mine with *grid* electricity, whereas scenarios are different for specific behind-the-meter (BTM) settings.

[8]For a different reading, see Coinshares' [16] argument that the China ban had a milder effect on Bitcoin decarbonization than usually estimated, and that the main effect instead was a reduction of seasonality in emissions (see also [3].

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

[10]Notably, De Vries' Dogecoin blog "Dogeconomist" (currently renamed "Digiconomist" [34]) contains a Bitcoin Energy Consumption Index (BECI) which is often quoted in news articles [35].

environmental impact. One area of disagreement is the object to which Bitcoin must be compared:

Countries: E.g. De Vries' BECI compares Bitcoin's annual carbon dioxide (CO2), electricity, and IT waste to countries such as Switzerland, Colombia and the Netherlands, respectively [38] (see also [28]).

Industries: The previous approach has been criticized for contrasting "apples with oranges," as many other industries also exceed the energy consumption of individual countries. It is argued that Bitcoin consumes significantly less energy than steel and aluminum instead [3]. There are also comparisons to gold [3], the banking industry [11], the global monetary system [16], Christmas lights [39], idle electric appliances [40], and others[11] which tend to be favorable to Bitcoin.

There is also disagreement about the best global denominator of which Bitcoin should be represented as a share of:

A share of global *electricity* consumption: E.g. De Vries' approach [38] (see also Oysti [11]).

A share of global *energy* consumption: Many [3], [25] argue that taking electricity consumption alone obscures conversion efficiencies (see also [11]).[12]

A share of global CO2 *emissions*: High energy consumption may not necessarily entail equally high emissions[19],[13] and climate change is a function of the latter, not the former.

As a share of global *GHG* emissions: CO2 emissions do not encompass the totality of GHG emissions [19], [28].

A debate has also raged regarding the basis of comparison to contrast Bitcoin's consumption/emissions with its value proposition. Alternatives include:

A per-transaction basis: This is the approach taken by De Vries[14] [38] (see also [28], [41]) and usually considers layer-1 (L1) transactions only, which has led to criticism [25], [42] (see per-dollar below). It has also been criticized because mining, not throughput, is the cause of Bitcoin's electricity consumption [10], [25]. Mining depends more on Bitcoin price than the number of transactions itself, which only has an indirect influence [25]. This may make this metric misleading, as it suggests that for Bitcoin's throughput to grow it needs to consume even more energy, a statement that may hold for PoS currencies but not for PoW ones [10]

A cumulative transactions basis: Because the energy expenditures to mine a present bitcoin secure the entire history of *past* transactions, and not just the coinage of the latest coin [42].[15]

On a per-dollar or per-coin *settled* basis: Given that layer-2 (L2) solutions such as the Lightning Network (or even changing Bitcoin's parameters) may allow Bitcoin to scale arbitrarily without increasing energy usage [10] this is often seen as a more adequate metric [25], [42].

A per-dollar or per-coin *mined* basis: This approach, suggested by Jones et al [17], offers a novel angle in the short run, but cannot be meaningfully applied over time as it neglects Bitcoin's decreasing emission rate.[16] It also assumes an "origin accounting" methodology (see below).

Cross [43] also identifies different carbon accounting theories used in the field of Bitcoin:[17]

Transaction accounting: Identifying the total carbon footprint of a block and dividing the total by the number of transactions contained in a block. See II.

Origin accounting: Running a genealogical analysis to consider the carbon emissions that were historically necessary to produce each block.

Maintenance accounting: Attributing the carbon footprint to the *holding* of a coin, as it is the demand for the coin that ultimately incentivizes mining. (see also [16])

Finally, different theories of causality are applied to Bitcoin's impact on the energy grid and the environment [46]:

Marginal emissions factors: The BMC is criticized for taking at face value miners' claims of being highly renewable when they are just located in a highly-renewable area and claiming the average grid mix.[18] If the additional energy demand following the miners'

De Vries follows a "top-down" approach, which observes miners' revenue and seeks to then estimate the share of income that is spent on electricity. This approach is usually considered unrealistic, and a "bottom-up" approach, whereby the hash rate is observed and the energy consumption per hash is estimated, is usually preferred [36], [37].

[11] "Aviation Industry, Marine Transport Sector, Air Conditioners and Electric Fans, Data Centers, and Tumble Dryers" [16, p. 12] (see also [3]).

[12] Natural gas, hydroelectric, coal, and nuclear generation have conversion factors of 44%, 90%, 32% and 32%, respectively. As Bitcoin mining is more reliant on the former than the average industry, its consumption of global energy is lower than its consumption of global electricity. In 2019, Bitcoin's electricity consumption would have placed it at the 28th place in a 70-country world ranking, but the 63rd in terms of *energy* consumption. This would more so be the case if indeed Bitcoin's energy mix is greener than the average sector's like advocates argue [19].

[13] According to Coinshares [16], bitcoin mining is responsible for a "mere" 0.08% of global carbon emissions (0.07% for McCook [19]), which compares to 0.14% of global energy consumption and 0.50% of electricity consumption.

[14] See De Vries' statement that a bitcoin transaction requires a carbon footprint of 424.40 kgCO2, and an electricity requirement of 760.90 kWh, equaling 940.616 Visa transactions, the average power consumption of a US household for 26.08 days and the weight of 2.59 iPhones, respectively [38].

[15] Imran argues that the key trend is not that energy consumption per transaction growing, but that total value secured is increasing [42].

[16] Usage of this metric forces the user to simultaneously argue that when the last bitcoin is mined Bitcoin's emissions will be infinite, and that approximately 90% of Bitcoin's climate damages have already occurred and the rest will be spread over an increasingly carbon-neutral energy grid.

[17] Along similar lines, Gallersdörfer et al [44] (see also [45]) identify transaction-based, holding-based and hybrid accounting models. We follow Cross' typology as it appears to be more comprehensive.

[18] Claiming the grid mix is misleading if the renewable energy (RE) in that mix has sold Renewable energy certificates (RECs) which the miner has not purchased. However, if no RECs were sold, a "marginal emissions" theory of causality is needed to criticize this claim.

installation is met with non-renewable energy sources, it is argued that the *marginal* consumption cannot be considered "green."

Average emissions factors: The alternative viewpoint posits that there is no reason to prioritize older energy consumers over younger ones, and that with regards to causing the need for electricity generation, all consumers are on equal footing from a causal point of view.

Whichever theory of causality is preferred, it is crucial to apply it consistently. If it is not legitimate to claim the average grid mix when it is highly renewable, it is hard to argue for the legitimacy of most journal articles, press and activism which also take mining pools' IP and attribute the average emissions of the corresponding area.

One may expect the upcoming introduction of carbon accounting requirements [47] to shed additional light on these debates.

c) Projections over time: Another area of controversy is projections of Bitcoin's future energy consumption [3], [28]. On one side, critics are concerned about the possibility that, if Bitcoin already consumes large amounts of energy while being an emergent technology, it could need even larger amounts to become as mainstream as advocates intend. On the other side, advocates argue that Bitcoin leads to a higher standard of living, which in turn is associated with lower emissions through the environmental Kuznets curve [3].

Advocates often point out that critics omit *halvings* in their projections [3]. Every 210,000 blocks (approximately 4 years), Bitcoin mining block rewards are cut in half, a process that is expected to continue until 2140, when the last bitcoin will be mined [11], [19]. Correspondingly, the incentive to mine (all things - including hash rate - equal) also drops, hence reducing energy consumption. For this reason, Carter and Stevens [3] (see also [25]) expect Bitcoin mining emissions to peak at 1% of global emissions at worst.[19]

Three related observations are in order. First, that peaking as a percentage of global emissions or energy/electricity consumption is not the same as peaking in absolute terms. Especially insofar absolute global energy consumption continues to grow, mining's consumption may grow below the global rate of growth and decline as a share thereof while increasing in absolute terms. Second, the expected threefold electrification of the world in the next decades may similarly lead global *electricity* consumption to grow proportionally much more than global *energy* consumption. As a result, Bitcoin's electricity consumption may peak significantly earlier *as a percentage of global energy consumption* [3]. Third, if Bitcoin's electricity consumption peak arrives significantly earlier than the world's electrification peak, this would result in additional GHG emissions than there would be otherwise.

d) Other impacts: Bitcoin is criticized as well for the electronic waste (*e-waste*) that mining might produce [48], [49]. Notably, De Vries and Stoll [50] provide the most pessimistic estimate of 30.7 metric kilotons (0.07% of all e-waste [25]). The underlying argument for this estimate is that, as more-efficient application-specific integrated circuit (ASIC)s enter the zero-sum mining market driving up the hash rate, older ASICs are pushed out of it as their costs increase and the break-even threshold is pushed upwards [16], [51]. However, many have criticized De Vries and Stoll's assumptions ([52]), pointing to the non-zero price at which supposedly obsolete ASICs trade, to the recyclability of ASIC components, and to how, under a buyer of last resort, bottom-feeding model (see V-B), old miners do not become e-waste as assumed but rather ancillary infrastructure for peak supply events (or are recycled) [52].

Lastly, Bitcoin is criticized on the grounds of its noise pollution [53], with little controversy being posited in this regard [28], other than pointing out that noise pollution is a subproduct of all data centers, and not specific to Bitcoin [54].

e) The underlying philosophical debate: The discussion of Bitcoin's environmental impact is also related to the controversy about whether Bitcoin has value at all [3], [5], [16], [25]. Bitcoin advocates argue that critics of the cryptocurrency surmise that its environmental impact is excessive because they assume that it has no value in the first place, but that they would not arrive to this conclusion if they recognized the services which Bitcoin provides [3], [5], [25].

This is closely related to the debate of whether *PoW* in itself provides any value relative to alternative consensus mechanisms such as PoS [16], [25]. Nonetheless, one should also note that despite PoW being energy-intensive by design, PoW is not a sufficient cause for "high" energy consumption. Bitcoin Core's energy consumption is "high" due to not only PoW, but also small block size and large block times. Although the majority of the Bitcoin community supports these features because they consider them preferable to the alternatives, not all do, and Bitcoin forks with a lower energy consumption have emerged by modifying these parameters [55], a factor that regulators should also consider when evaluating possible PoW bans.

C. Regulatory approaches

As is the case across most policy fields, decision-making on laws and directives might prohibit, constrain, or promote the usage of a public or private good. A similar case can be made for digital and distributed ledger technologies, although the poles between which governments are currently positioning themselves could hardly be more different. China started to ban Bitcoin, that is, exchange and/or activities that involve bitcoin financing between fiat money or coin substitutions back in 2017 in an attempt to maintain consistency in their regulatory framework [56]. In September 2019, the country decided to fully ban crypto assets which include mining activities [57] under the premise to fight back against financial crimes and

[19]According to McCook [19, p. 14], "it is likely that Bitcoin's emissions have already peaked, considering the mass migration away from worst-in-class Chinese coal, to best-in-class (or at least 50th-percentile) Natural Gas, an emissions drop in emissions of between 70 to 80% per unit of energy, despite energy use trending upwards. In other words, for emissions to return to pre-China migration levels, energy expenditure would need to grow three-fold, and the demonstrably false assumption that there will never be any further efficiency gains in mining hardware."

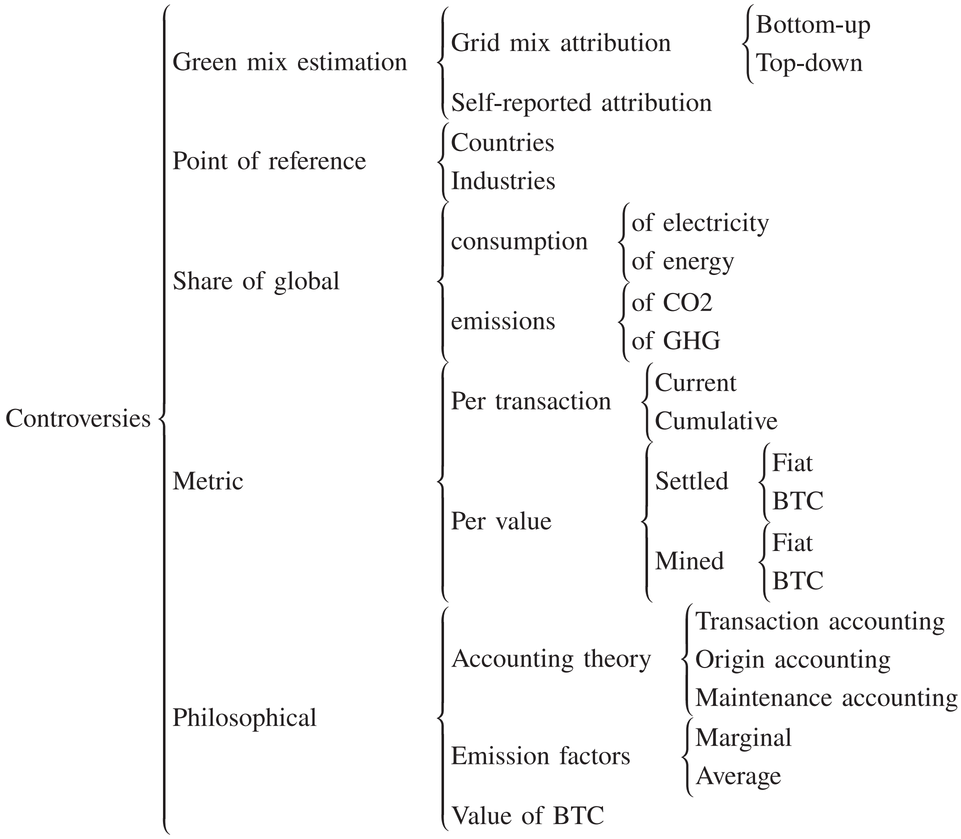

Figure 1. The controversy about Bitcoin mining's environmental impact.

capital flight and to maintain economic stability via greater state intervention [58].

An alternative approach to develop and therefore regulate the above-mentioned technological advancements has been chosen by the US. In March of 2022, the Executive Order on Ensuring Responsible Development of Digital Assets was signed. While recognizing the importance of DLTs, the order calls for higher standards in their application in order to mitigate a variety of risks, ranging from financial threats and risks to customer and investor protection, to climate and environmental impacts [59]. This approach called for more research, which resulted in works such as the Report on Climate and Energy Implications of Crypto-Assets in the US ([28, p. 3]), that paid special reference to mining based on "clean energy" to avoid GHG emissions.

Within the European Union, the situation is more complex. A uniform regulatory framework has been introduced for all crypto-assets in the Union to improve consumer protection, increase market integrity and financial stability, and prevent all criminal activities such as market manipulation, money laundering and terrorist financing [60]. However, PoW mining has been criticized by the European Union (EU) commission for its high electricity consumption, especially in the wake of energy shortages after Russia's reduction in gas supply. Discussed has been a possible energy efficiency label for PoW mining and a grading mechanism likely to encourage a switch to what is perceived to be a more environmentally-friendly crypto-system, namely PoS [61], [62].

III. Limitations of renewable energies

A number of limitations prevent renewable energy sources (RES) from being as widely adopted as the vision for a renewable world. Generally considered, the problem is one of profitability [3] and intermittency [63]–[65]. RE generation has traditionally not been as cost-efficient for producers to engage in this activity massively [3]. Governments resort and have resorted to subsidizing and similar strategies to compensate for this issue. However, this is costly and entails problems of its own. At present, renewable energy generation continues to become increasingly more efficient and less costly, with the trend being expected to continue [3]. Nonetheless, at high levels of renewable penetration, renewable energy generation displays a series of issues, also impacting profitability [3].

A. Imbalances

For variable renewable energy (VRE) generation, the most well-known manifestation of these issues is the so-called *duck curve* [11], [66], [67]. This phenomenon relates to the fact that the sun shines during the day only and that wind (while more unpredictable) tends to blow more heavily at night. In contrast, the energy supply peaks in the late afternoon and early evening as people turn on appliances upon returning home [67].

This, other forms of renewable volatility, and other sources of intermittency (e.g. transmission constraints and extreme weather events) lead to imbalances that may manifest in the form of negative pricing and/or *curtailment* at high levels of renewable penetration [14], [19], [21], [25], [64], [67]–[70]. This issue is particularly autochthonous to electricity, as the feature that most markedly distinguishes it from other commodities "is that it must be consumed just moments after it is produced" [51, p. 6].

The fundamental problem of imbalance[20] between VRE sources that fluctuate exogenously and electricity demand that is not constant throughout the day, week, or year, means that one of the features of a well-functioning energy system is *load following*, such that the network never overloads nor blacks out [3], [71].

However, VRE generation is usually not something that can be increased at will (and can only be decreased at will by curtailing, which entails a significant opportunity cost), as it displays fluctuations of its own, i.e. intermittency [3], [11]. Consequently, although supply and demand sometimes coincide, they often do not, creating a mismatch [3], [5]. These fluctuations are often *sudden*, further aggravating the difficulties caused by the mismatch [51]. Demand-side fluctuations may be sudden as well, for instance, due to abrupt heat or polar waves [51].

These mismatches are problematic as they affects grid resiliency. In the absence of alternative solutions, preserving resiliency requires capping the contribution of VRE to the grid at a rather low percentage, and supplementing peak load with non-renewable sources. This limits the extent to which decarbonization can be advanced. Some partial solutions to these issues are referred to in Table I.

Note that DR programs may be considered a form of sector coupling (see [78]). Furthermore, storage and demand-response programs are subtypes of so-called "power-to-X" solutions, i.e. the practice of converting or storing surplus electric power during excess supply periods [21], [79]–[81].

B. Funding challenges

In addition, renewable energies suffer from other problems, notably financial ones. As an example, "solar value deflation" makes it hard to convince investors and developers to build solar plants [25, p. 6] despite how necessary these investments are for the energy transition (IRENA in [25]).

An additional problem is emerges as the construction of many renewable energy generation facilities is often not finalized on time, if at all [25], [82]. Moreover, these facilities often need to be located in remote places, which means that they are further away from the sources of demand, leading to additional transmission investment costs [51]. More long-distance transmission furthermore means more transmission losses [3], [16], reducing profitability.

This is also related to another difficulty faced by renewable energy projects, namely connection queues for either technical reasons (infrastructure pending to be finalized) or regulatory reasons (connection to the grid not authorized). [23][25], [67], [82], [83]

Finally, there is an issue of spot price volatility in energy markets, which is aggravated by the regulatory connection queues themselves. Bastian-Pinto et al [82] point out that while waiting for the queue to sell at a regulated price to be cleared, an energy seller faces the option of selling energy in the spot market, but at the cost of facing price volatility risk. If the seller chooses not to come onstream to the grid ahead of this date, however, the likelihood of it meeting the contracted date decreases [82].

C. Prospects

The practices and technologies mentioned above emerge as fundamental from the various International Energy Agency (IEA) goals identifying the key challenges toward decarbonization.[24] Nonetheless, humanity continues to face important obstacles in its search to meet these goals of renewable penetration, grid resiliency, electrification, etc. [85], [86]

In this context, PoW mining emerges as an alternative that can provide additional income and, notably, *ancillary services* ("*power-to-bitcoin*"). Ancillary services are auxiliary services designed to provide stability to the energy grid and may include reactive power and voltage control, frequency control, scheduling and dispatch contingency energy supply reserves (for outages), flexibility energy supply reserves, and flexible energy demand load [25], [51], [87]. Mining may fall into this category.

IV. Particular characteristics of PoW mining

As an economic activity, PoW mining in general (and Bitcoin mining in particular) stands out for a number of characteristics that make it a unique energy buyer [67], namely:

Flexibility of load: From a technical point of view, Bitcoin miners can be turned on or off at a moment's notice [11], [66], [67], with sub-second responsiveness [25], [51], i.e. a near-instantaneous manner,[25] there being neither inertia, cooling,[26]

[20]Strictly speaking, the grid operator's very role is to prevent imbalances by matching supply and demand, e.g. by curtailing supply. There is however an imbalance in a broader sense. There are inevitable deviations from contracted positions due to imperfect forecasts and unpredicted events (outages of power plants and lines), which the system operator corrects by calling upon reserve capacity that has been contracted upon. Although the cost of this capacity is partially recovered through grid fees and penalties for deviating from schedule, around two third of the costs are socialized in the form of higher prices [70].

[23]Rand et al [83] find that the average US commercial power projects spent approximately 3.5 years waiting for connection approval between 2010 and 2020, and that connection wait times are following an upward trend. The report finds 680 GW of zero-carbon generation capacity stuck in queue.

[24]Note that renewable generation is not entirely carbon-free. The manufacturing and deployment of solar panels and batteries, for instance, requires energy-intensive processes (as well as other environmental and even labor costs) [69]. Nevertheless, renewable energy generation displays significantly lower life-cycle emissions compared to fossil generation [84].

[25]Lancium [87] in Mellerud [51, p. 45] places this reaction time in 5 seconds, which "is on par with the fastest reacting peaking plants".

[26]Bitcoin mining entails cooling costs, but cooling costs do not increase with flexibility of load, and may in fact decrease with it [51].

Strategy	Description	Challenges
Transmission	Importing and exporting, i.e. transporting energy from places where there is excess supply to places where there is excess demand, is one of the most effective ways of balancing electricity markets [51], [67], [72].	Transmission lines have limited capacity and experience congestion,[21][3], [5], [67], [73] are struggling to keep up with electrification trends [72], suffer from energy losses proportional to their length and require substantial initial investments [3], [16], especially in relation to remote locations where renewable generation is often most efficient [16], [51]. Energy that cannot be transmitted is defined as "stranded."
Capacity expansion	Investing in excess RE infrastructure to be able to meet demand even in times of low supply.	This can be seen as over-building or over-investing, which affects the sector's profitability, as it leads to low or even negative prices in periods of high supply (or generally inactive backup plants), hence requiring government subsidies [51], [66], [67] and curtailment, which is usually intentionally designed-in in capacity expansion projects [74].
Curtailment	If RE production infrastructure has been built, the energy produced is sent to waste to avoid problems such as overloading transmission capacity or negative prices [19], [25], [65], [68], [75].[22]	Curtailment has as an opportunity cost in terms of energy not sold, which decreases the profitability of VRE generation. This is especially an issue as curtailment is projected to increase over time [70], [76]
Storage	Storing energy when there is excess supply and using it when there is excess demand. This may be done through batteries (see VIII) or other methods such as *pumped hydroelectric storage* [51], [67], [77].	Batteries and other storage solutions are expensive [3], [51], [77] and have limited capacity, which restricts the prospects of using them at scale (see VIII-D).
Demand-response programs	If control of energy supply is relinquished, grid operators must move from traditional energy grids where consumption is an exogenous variable and seek to influence electricity demand patterns to match supply patterns ("load balancing" [19]). This is known as a flexible load response ([25], [63], [67], which may be voluntary, the result of a power purchase agreement (PPA) or the result of a demand-response (DR) program where the energy customer is compensated for not consuming energy during a peak event [51], [73].	Most loads are not flexible enough to allow for this at very large scales without significant costs or opportunity costs.

Table I
An overview of some of the main strategies to counter problems of imbalance spurred by VRE.

warming up requirements nor other reaction costs [51], enabling high flexibility of load, which supports grid stability [25].

When flexibility consists of being able to reduce, not increase, energy demand, a factor behind flexibility of load is the *availability* of load. A load resource is "available" if it is continuously demanding energy, and hence can be turned off. Modern ASICs are usually mining at full capacity[27] or even overclocking, meaning they produce a "reliable and stable load with great availability" [51, p. 45].

For grid resiliency, availability must be a constant in the long run: Bitcoin mining is suited to provide this as miners tend to have a long time horizon[28] and because Bitcoin mining's "cash-flow break-even level is usually significantly lower than the return on investment (ROI) break-even level" [51, pp. 50–51].[29]

Interruptibility: The Bitcoin protocol's parameters are designed for a bitcoin to be mined every 10 minutes. If the protocol on average[30] is taking more or less time to find the nonce, the "difficulty level" is adjusted for the mean to slide back to 10 minutes. However, the expected block time is *always* 10 minutes: if 9 minutes have passed since the last block was mined and no new block has yet been found, the expected block time is still 10 minutes, not one minute [19]. Due to this, and because mining consists of guessing the nonce by trying quadrillions of possibilities (millions of terahashes) per second, of which all but one are incorrect, if the mining process is interrupted, *no work is lost*.

In other words, mining relies on *non-time sensitive computation* [51]. Together with quick reaction time [51], [90], this enables an immediate switching of outputs [28], [82]. Quick reaction time and near-zero reaction costs (no output lost)[31] entail high interruptibility [11], [25], [51], [63], [67].

Portability/mobility: Bitcoin mining is location-agnostic [11], [67] and requires sinking little costs in immovable goods. ASIC and other mining equipment can be transported with relative ease, as can most supplementary hardware. Mining can furthermore operate in several kinds of geographies and climates without a grid connection (only an electricity source is needed [19]) [5], [25], unlike most other industries [51]. Bitcoin's portability is additionally enhanced by the *modularity* of mining: the existence of modularised and shipping-container-based solutions allowing for mining operations anywhere on earth [3], [5], [19].[32]

This is not to say that there are no immovable investments, such as land, rack space,[33] among others. Nevertheless, the speed with which mining migrated to other locations e.g. after the China ban on mining [19], as well as the seasonal character

[27]Unlike traditional data centers [66].

[28]Due to ideological and economic factors [88], [89], but also to the fact that collateral is required to enter into PPAs: the need to earn back collateral increases the need for long-term planning [51].

[29]Volatility negatively impacts the stability of availability, however (see VII-A).

[30]The difficulty level is analyzed every 2016 blocks.

[31]Freier and Ibañez [91] find that there may be an economic cost to mining interruptions when mining at very small scales, because stability of income requires connecting to mining pools, which often reduce rewards for miners that provide hash rate in interrupted manners.

[32]Mobility also strengthens the resiliency of the Bitcoin network itself [5].

[33]Quirk [66] notes that rack space requirements are reduced with liquid immersion cooling, enabling more dispersed, cellular mining facilities in remote locations.

- Mining
  - Flexibility of load
    - Reliability of load
    - Availability of load
      - Stability of load
      - Reliability of load
      - Long time horizon
  - Consumption-level granularity
    - Interruptibility
      - Quick reaction time
      - Near-zero reaction costs
    - Portability
      - Location agnosticity
      - Movable goods
      - Geography independence
      - Modularised solutions
      - Unncessary grid connection
      - Low labor intensity
      - Transferrability of output
    - Price sensitivity
      - Bitcoin price sensitivity
      - Cost sensitivity
        - Few inputs
        - High sensitivity to electricity prices
      - Granularity
      - Information completeness
    - Scalability
  - Non-rivalrousness
  - Non-correlation
  - Heat output

Figure 2. Salient characteristics of Bitcoin mining identified.

of mining operations in China [3], show that mining is also geographically flexible to a significant extent from an empirical point of view [51].

Moreover, the bitcoin mined need only an internet connection to be transferred, with no need for pipelines, trains, trucks, flights, or other investments to transport the produce to a different location; there is only a need to ship ASICs and cooling equipment once [51].[34] This enables high responsivity to market conditions. Furthermore, it enhances the road of ancillary services provider, as (unlike most sources of demand) flexible load response services need to be located near production areas [73], [92]–[96]. Bitcoin mining furthermore is not labor-intensive, which allows placing the mining farm far from urban centers.

Cost and price sensitivity: Bitcoin mining has shown itself to be one of the world's most price- and cost-sensitive industries [97], with prices being "invariant across times and locations" [25]. This cost sensitivity is indeed the factor behind the fierce race for cheap energy in the Bitcoin market. Importantly, bitcoin mining is an activity with few inputs and outputs and, among the inputs, a substantial part of the expenses is directed to electricity payments, meaning the cost sensitivity is attuned to electricity prices in particular [51]. Furthermore, cost sensitivity is expected to continue to increase in the years to come (see IX-C).

This all means that bitcoin ASICs are an asset more suited to react to volatile electricity costs, and more suited to be placed at the generation side, than conventional ones [68]. Moreover, as different ASICs have different profitability profiles, this provides for significant complementarities with multiple niches and patterns in the energy system [25] (granularity [51]). Furthermore, these different break-even points are *known* by the various actors, which facilitates more efficient behavior [25].

Scalability: The scale of Bitcoin mining operations is not pre-established, and can be adjusted according to each setting's specific needs, "from solo home mining[35] to gigawatt industrial operations" [25, p. 5][13]. This is also a result of Bitcoin's energy intensity [51] and means that the Bitcoin industry may be large enough to act as a shock absorber for the grid [11].

Consumption-level granularity: The combination of energy intensity, interruptibility, and scale achieved through the

[34]Note that, "in the first years of ASICs mining, miners were significantly less geographically flexible than they are now, since they had such big advantages of locating themselves in China, close to their suppliers of ASICs," but this is no longer the case, as "the technological improvement rate of ASICs has drastically slowed down, leading to a longer life-time and thus less importance of having the newest gear." [51, pp. 48–49] (see also [42])

[35]Note however that a minimum scale is required to participate in DR programs. Mellerud places this in 100 kilowatts, which approximates a mining farm comprised of 70 Antminer S9 [51].

combination of ASICs with different break-even points results in a "load that can be rapidly adjusted up or down with extreme precision, at no extra costs" [51, p. iii] (see also [90]). This comes in contrast to hard binary alternatives consisting of either consuming at full capacity or shutting down consumption entirely. The former is called a controllable load resource (CLR) and the latter a non-controllable load resource (NCLR) [51], [76], [87].[36]

Non-rival energy consumption: Although mining is certainly an energy-intensive activity, it may be misleading to only consider the energy consumption *level* and not *which* energy is consumed. The energy load from mining does not necessarily cause the need for more generation of energy (and emissions) to match this load. For one, and as a result of the flexibility of load, mining can[37] be performed with otherwise curtailed energy [19], [65], stranded oil and gas [11], and flared gas [11], [66] (see V). This means that miners do not necessarily compete with other consumers of energy, nor generate *additional* emissions. Rather, they may consume energy that had already been generated or act on the basis of emissions that would have been emitted anyway [19].

Uncorrelation: Bitcoin mining in particular may provide an additional source of both profitability and stability of income for renewable energy sellers, as global bitcoin prices/hash rates and electricity prices "follow distinct and uncorrelated stochastic processes, which enhances the value of this option to switch outputs" [82, p. 2] (see also [71]).

Heat: The process of producing the output of hashes requires the input of energy. The law of conservation of energy entails that there will be another tangible output to the process, namely heat [53]. As a result of the challenge to dissipate significant heat loads, the mining sector is currently developing cooling procedures [66], [97]. However, heat also has many other applications and currently there are numerous innovations to recycle heat and assign other uses to it [97], including replacing some residential (e.g. hot water and space heating for households and schools) and commercial (e.g. greenhouses) heating elements with bitcoin miners [14], [25], [53], [98].

V. Applications

As a consequence of the characteristics listed in IV, mining can provide a series of services to the energy sector. In particular, these consist of ancillary services, the consumption of stranded resources, the prevention of gas flaring, and the provision of additional funding.

A. Sectors

Wind energy: Wind energy suffers from the duck curve problem. Through flexible load response, bitcoin mining can provide ancillary services in the form of a flexible load resource that may be shock-absorbing [11], [96], which may increase profitability by providing an alternative to selling energy at very low prices in times of o supply [11] (see also [90]). This form of mining is typically done on-grid but behind the meter (next to generation), leading to no increases in transport infrastructure.

Solar energy: Solar energy also suffers from the duck curve problem. PoW mining may provide ancillary services in the form of flexible load response as well [90], [96]. There is significant evidence that cogeneration systems based on solar generation and cryptocurrency mining significantly increase the profitability of the enterprises [20], [77], [96], [99], [100].[38] This form of mining is also usually done on-grid but behind the meter.

Nuclear energy: In principle, nuclear energy supply patterns are more akin to oil and gas than wind and solar, in that generation can be increased or decreased to match demand patterns [102]. However, there are limitations to this. There are strong technical and economic reasons why operating a nuclear power plant in a load-following manner may not be cost-effective, essentially because of reactor cooling costs, which impact the variable cost of selling nuclear energy [102]. Considering that the minimum price at which an energy seller is willing to sell its output is its variable cost, in periods of excess energy this may lead to negative prices, which severely harm the sustainability of the business model. PoW mining may also provide ancillary services in the form of flexible load response in this scenario, when it is more efficient to mine than to operate the power plant in a load-following manner (for nuclear-based bitcoin mining with a stable load, see [103], [104]). Nuclear reactors have already been suggested as a power source for data centers [105].

Waste gas recovery: venting and flaring: Two very significant sources of methane emissions to the atmosphere are landfill gas and stranded natural gas.[39] Landfill gas is approximately 50 % methane [106] and is frequently flared [107], the output of which is also mostly methane due to inefficient combustion[40] and strong winds [19].

Stranded natural gas is excess gas found around oil wells or in excess of a gas well's transmission capacity, which is not profitable or possible to process or transport for consumption elsewhere [3], [19], [66], [107]. This gas is also frequently flared [109]. If not flared, stranded and landfill gas is vented, which leads to even greater methane emissions [11], [30], [110].[41]

Considering the characteristic of portability mentioned above, containerized mining and generator solutions [19] are already

[36]Mellerud describes how, in Texas, the NCLR status is harder to acquire under the regulator but provides additional benefits to the market participant [51].

[37]And has been, having led to a reduction of curtailing in Yunnan (China) in 2016 [19].

[38]Eidt et al [77] also find additional financial benefits of solar energy-bitcoin cogeneration not related to flexible load response (see also [101]).

[39]There are also other initiatives to use gas "that would otherwise go to waste" for mining purposes [5, p. 8].

[40]"Flared natural gas burns the methane producing as a byproduct CO2. This reduces theoretically the CO2 equivalents, but the efficiency of flaring varies largely, in some cases up to 70 percent can escape into the atmosphere" [11, p. 41]. This also applies to other volatile organic compounds (VOCs) [108].

[41]Wright [110] estimates that 70% of US landfills are freely emitting methane into the atmosphere, because they are too far from cities for methane to be processed (burned or refined into natural gas).

being deployed [3], [19], [28], [51], [108], [109], [111] to exploit this near-free source of energy,[42] thereby transforming methane emissions into carbon dioxide emissions by means of more efficient combustion.[43]

Under the assumption that methane is worse than CO2 in the fight against global warming,[44] Bitcoin mining not only provides an additional stream of marginal income for energy companies per barrel of oil produced,[45] but also adds to the load without compromising the existing energy supply. It furthermore provides a public service, by reducing the carbon footprint even where the total amount of gas extracted remains unchanged.[46] Indeed, methane-based bitcoin mining is reported to reduce GHG emissions by 50% to 63% compared to traditional flaring, on top of making use of otherwise wasted energy [19], [66], [109], [111].[47]

This sort of mining, which is typically done off-grid (also not requiring additional transmission infrastructure), is usually *not* flexible, and runs 24/7 (high uptime), as flared gas does not follow the intermittency patterns dictated by the sun or wind. On the other hand, gas operations may be shorter-lived.

The potential of methane-based mining is even recognized by the US OSTP, which maintains that it is "more likely to help rather than hinder U.S. climate objectives" [28, p. 24]." In this context, note that [11, p. 41] "some suggest that the U.S. and Canada have enough flared natural gas to run the entire bitcoin network." (see also [109])

Others: The above includes some of the most salient applications of bitcoin mining in the renewable energy sector, but there are of course numerous others. Notably, BTM hydroelectric mining is substantial in the bitcoin mining market [5]. Although its share is expected to fall versus wind and solar over time, it represents the main renewable energy source for miners at present. The mining is usually done with curtailed hydroelectric power in areas with excess hydro capacity (e.g. [114] but follows a much higher uptime model than solar and wind energy (curtailment is the result of just a few hours of intense sun or winds [3]), leading to the usage of more modern ASICs. [67]

Other renewable energy sources are also used. Examples include biogas[48] and geothermal.[49]

Finally, bitcoin mining may have other applications at the intersection of energy and sustainability that go beyond renewable penetration. Because competition in the bitcoin mining space is fierce,[50] mining is a sector characterized by fast innovation, a fact accepted even by bitcoin critics [21]. As a result, Imran [21] postulates that, by creating strong competition in terms of computing power, bitcoin mining has a positive externality: it incentivizes the development of chips that create more computing power per unit of energy dissipated such that Koomey's Law[51] is outpaced. Other positive externalities, such as arbitraging toward a global energy price, have been identified [42].

B. Business models

Bitcoin mining can hence supplement the energy industry in a number of ways. In this section, we discuss various possible business models that are adopted at the intersection of these two industries, which may have a significant potential for growth.

1) First or last resort:

Buyer of first resort: Bitcoin mining may provide not only an additional source of income for energy producers, but also a primary source of demand which pays more than the alternatives (mainly selling to the grid) [71], [82]. Although this may be construed as displacing other consumers, this is not necessarily the case. Because of the above-mentioned connection queues, a power plant may spend years without being able to sell any energy to the grid at all, which severely harms profitability and, if anticipated, may deter the undertaking of these projects to begin with. Conversely, Bitcoin mining may provide a source of demand (and hence revenue) throughout the connection queue, increasing the economic viability of the project and, if anticipated, stimulating the installation of the plant in the first place. [82]. It also facilitates the anticipation of the construction, which makes it more likely that the plant will begin selling energy to the regulated market at the contracted date, as it provides extra time to adjust to unanticipated delays in construction [82].

[42]This energy source is sometimes negatively priced due to savings on flaring penalties [109] and production stoppages that ensue as a consequence of flaring caps [107].

[43]"Bitcoin mining (...) can burn the methane with a 99 percent efficiency, reducing substantially the risk of leakage into the atmosphere." [11, p. 41].

[44]According to the Intergovernmental Panel on Climate Change (IPCC), the global warming potential (GWP) "of methane are about 60, 28, and 5, respectively, for time horizons of 20, 100 and 500 years" [64, p. 15] (see also [3], [11], [19], [30], [111]). However, the standard way of accounting for GWP (GWP100) has been challenged with because it fails to account for GHG emission *rates*, leading to alternative metrics such as GWP* [112], which has an "exculpatory" effect on some methane emissions, relative to GWP100 [113]. These disagreements cannot be solved through scientific inquiry, as the underlying controversy is a political contention about attribution of responsibility, which depends on value judgments [113]. Statements about methane relative to other GHGs should hence be made with care.

[45]We should note however, that if an additional source of income prevents a drilling site from shutting down or stimulates additional hydrocarbon *exploration*, the effect from Bitcoin-based gas flaring might not be net-decarbonizing (see also [5], [13], [108] and IX-C).

[46]An additional incentive for oil and gas companies to permit bitcoin mining with flared gas is simply to get carbon emissions "off their books," which in itself does not have a direct net decarbonizing effect. However, indirectly it does produce a decarbonizing impact due to the efficiency gains in combustion produced by transferring gas emissions to miners [5].

[47]Similarly, Coinshares [16] argues that carbon emissions from flare mining are already negative and equivalent to 5% of Bitcoin's global positive emissions already.

[48]Malfuzi et al [23] furthermore show that in countries with high prices of electricity and natural gas, biogas mining is better suited for the generation of electricity and for its consumption in cryptocurrency mining, which they deem to have environmental benefits.

[49]This is most notably experimented with in El Salvador. Kumar [115] finds that Bitcoin mining defeats the energy transportation problem that characterizes geothermal energy generation, although ASIC heating is significantly challenging in this setting.

[50]McCook [19] argues that bitcoin mining companies compete fiercely in two dimensions: technological efficiency and managerial approaches. This is also shown by the speed and minimal disruption with which large Chinese miners were able to relocate their operations as the regulatory landscape became unfavorable.

[51]The trend for the number of computations per joule of energy dissipated to double approximately every 1.5 years [116].

- Low carbon mining types, classified by
  - Energy source and model
    - VRE
      - Peak-shaving
      - Valley-filling
      - Load-building
    - Other RES
      - Hydroelectric
      - Nuclear
      - Geothermal and others
    - Methane
      - Pay for the gas
      - Pay for the equipment
      - Others
  - Location relative to grid
    - On grid
      - FTM
      - BTM
    - Off grid
  - Miner-generator relationship
    - Mere proximity
    - Contracting
    - Vertical integration
  - Pricing model
    - Standard consumer
    - PPA
      - Standard
      - Ancillary services DR programs
    - Price responsiveness
  - Uptime
    - Low uptime (bottom-feeding)
    - High uptime

Figure 3. A typology of low-carbon mining models per defining factor.

Buyer of last resort: Bitcoin mining may become profitable when there is excess energy relative to the demand and prices are extremely depressed, or when there is excess energy relative to transmission capacity. [5], [67], [71]

2) Uptime:

High uptime model: Typically, the model where Bitcoin miners constitute a buyer of first-resort is achieved with the most efficient, last-generation ASIC miners, which run almost 24/7 and provide the lowest energy cost per hash [3]. Peak-shaving models are also high uptime.

Bottom-feeding (low uptime model): Less efficient Bitcoin miners, i.e. ASIC miners that have been overcome in hash rate capacity by newer machines, are typically pushed out of the market by the latest technology. The hash rate of the newer ASICs dilutes the hash rate of the older ASICs, thereby pushing their break-even point to lower thresholds than before. In other words, the introduction of new ASICs to the market means that older ones stop being profitable at lower energy prices than previously [11]. However, this also means that, as energy prices become lower themselves, ASICs that were not profitable up until that point become profitable to turn on. These miners may be turned on intermittently to suck excess energy (VRE generation facilities as "ASIC retirement homes"), thereby providing an ancillary service, stabilizing the grid and increasing profitability [11].

3) Location of the miners:

BTM: BTM mining consists of placing the miners directly at the renewable energy plant, which reduces transmission and distribution costs [13], [51], [67], [90], [96]. It compares to mining in FTM.

FTM: FTM mining consists of plugging into the grid as a regular consumer, being subjected to the same prices as other customers, and consuming the same proportion of green to non-green energy as them. [90], [96], [117]

4) Pricing model:

Power Purchasing Agreement: A PPA provides a fixed price to the miner. This provides stability to the miner, which enables forecasting. This provides other indirect benefits to the miner, such as facilitating the attainment of external funding. A PPA may be combined with an "option" right for the energy seller to require that the buyer turns off their ASICs,[52] hence providing flexibility (see V-B5). However, in areas of high renewable penetration or frequent extreme weather events, PPAs will be priced above the median energy price [51].

A PPA may be a

> **Standard PPA:** A standard PPA provides a fixed price and energy quantity for a given amount of time to the customer [118], presenting no particularities for the case of a customer which is a Bitcoin miner.

[52]In exchange for lower prices in non-peak demand periods [76] as well as compensation for turning off the ASICs [76].

Ancillary service demand-response programs: The miner locks in a certain capacity for a given price, selling an "an option on this capacity in the day-ahead ancillary service markets" [51, p. 42], with CLRs getting paid more than NCLRs. During emergencies, the grid operator "deploys the load resources", meaning it exercises the option to turn them off" [51].[53]

PPA-based mining is usually FTM [51].

Price-responsiveness: In a price-responsive model, the energy seller sells energy to the miner at the miner's break-even point, doing so when the break-even point is above the market price. If the market price is above the break-even point, it does not sell to the miner but only to the market [51]. This may reduce the energy prices paid relative to a PPA because extreme price events do not affect the miner's price [51], and furthermore reduce other costs such as cooling costs.[54] From the point of view of the energy seller, this model "ensures" a source of local energy demand at a given minimum price, also providing additional foreseeability.

Price-responsive mining is usually BTM [51].

5) Relationship between miner and renewable energy producer:

Mere proximity: The most basic possible relationship between a renewable energy producer and a miner is a non-existent formal relationship, with the miner nonetheless establishing in the proximity of the renewable energy plant [13], [68]. This may be done in order to achieve ESG goals, to take advantage of low prices in the energy grid in peak supply periods, or a combination of the two. This relationship is the simplest type and may allow for efficiency gains [68]. Nonetheless, it exposes the miner to instability in the energy price and does not give the producer a say on when the miner should be on or off.

Direct contracting: At present, an increasing number of miners are establishing formal relationships with renewable energy producers [3], [51]. A PPA is usually established with the energy producer, allowing for some stability of pricing, which the miner may prefer for its own reasons or to appease its funder's (e.g. a bank's) concerns to release funding. On top of the PPA, the miners sell an *option* (or "insurance") right to the renewable energy producer. This gives the producer the right to request the miner to turn off its ASICs for a fee, for a number of days per year [3], [51]. The model gives the producer a say on whether the miner should be on or off, enhancing efficiency by giving the energy supplier the possibility to occasionally influence demand so as to allocate energy, at least on some periods, to its more efficient use. Nevertheless, insofar as it is not optimal or possible to exercise the option right, energy consumption decisions might deviate from the most efficiency-maximizing behavior. Furthermore, transaction costs are not internalized.

Vertical integration: Although mostly a theoretical possibility until the present day, the possibility of a renewable energy producer directly engaging in mining [82], [91], [119], or a miner inserting itself in the renewable energy sector [119], [120] (see also [121]), has been considered. This business model requires prior knowledge diffusion and the building of expertise, and introduces further economic calculation requirements on the energy producer's side. However, this introduces the possibility of allocating each specific electron to its most revenue-maximizing use (use it, store it, mine it [67]), unlocking even further efficiency effects at least theoretically.

Vertical integration may provide a direct stabilization lever for a renewable energy producer's income, acting as a *real option* instead of an option contract [82]. The miner would have the capacity to arbitrage between energy prices and bitcoin prices [67]. It may also ease the capital availability and reputation issues of miners [5], [13], [31], [119].

6) Gas mining models: Vazquez and Crumbley [111] identify two main business models for flare mining:

"Pay for the gas": The miner pays for the collected gas used on the well site and keeps the mining proceeds [111].

"Pay for the equipment": In exchange for rental and service fees, the miner provides a fully equipped data center with generators to the hydrocarbon company, who keeps the mining proceeds [111].

Others: Other models identified by Vazquez and Crumbley include "mobile market hubs" to ease pipeline constraints [111, p. 5].

7) Portfolio greening: Although beyond the scope of the current paper, a portion of the literature has concerned itself with the issues of proving that a bitcoin portfolio is "green" and incentivizing green mining, regardless of whether this favors renewable penetration or not. We briefly summarize existing proposals:

RECs, guarantees of origin (GOs), and carbon offsets: Purchasing RECs and GOs is a standard mechanism that a miner may employ to reduce its carbon footprint [3], [14].[55] Both bitcoin miners and other buyers may also calculate the carbon footprint of their bitcoin holdings and purchase carbon offsets to compensate therefor [3], [16], [30], [122].[56]. A disadvantage of carbon offsets is that they require knowledge of the entire broader energy mix of bitcoin mining with the associated carbon accounting issues [3].[57]

[53]Mellerud [51] reports that the deployment of the load resources leads to an average uptime of 99.7% in Texas, instead of 100%. With this level of uptime, liquid cooling is required.

[54]In Texas, the price-responsive model leads to an uptime of 85%, where downtime coincides with the hottest periods of the summer. This strongly minimizes the necessary expenses in liquid cooling[51].

[55]As it is not possible to trace individual electrons through a grid with a varied energy mix, purchasing RECs is an approximation to showing that a given amount of energy has been sourced renewable, and indeed stimulates renewable buildout through a demand effect [3].

[56]Note however that Corbet et al [12] find a negative correlation between bitcoin price and carbon credits. Similarly, they find no significant relationship between the bitcoin market and the largest green energy exchange-traded funds (ETFs). The authors interpret that this suggests that there are no positive externalities from Bitcoin to tackle climate change.

[57]Cross [122] argues that there exists significant controversy about carbon offsets' reliability [122]. Furthermore, carbon accounting requires an investigation of the different forms of accounting for bitcoin mining emissions [43], [123] (see II-B).

Incentive offsets: Cross and Bailey [122] argue that carbon offsets are neither reliable nor standardized, and that it is preferable (both more profitable and more effective) to offset through incentives. Bitcoin mining has the particularity that it is a zero-sum game, and any additional hashrate reduces rewards for existing miners. It follows that any investment in green hashrate acts as a Pigouvian tax on existing hashrate, and hence a bitcoin investor may offset their carbon footprint entirely by co-investing in green bitcoin mining in proportion to their bitcoin holdings (in size *and duration*). This also acts as an argument for authorities to provide tax breaks to green mining [65], [68].

Others: An alternative to RECs and GOs, which aim at indirectly certifying that the miner used renewable energy in the mining process, and carbon offsets, which seek to compensate the investor's carbon footprint, is to purchase certificates for sustainably mined bitcoin. This acts as an offset for an investor's bitcoin holdings that does not require carbon accounting.[58]

Other suggestions to stimulate green mining include colored coins, i.e. marked "UTXOs from blocks discovered by mining pools with a known and sufficiently favorable energy mix" [122, p. 6] (see also [21]). This has some significant disadvantages, such as breaking bitcoin's fungibility, as well as facing technical and accounting challenges [122].

VI. Potential impact

Mining is already impacting renewable energy generation and energy grid management [3], [19], [51], [108], [109], [111], [122]. Although the scale of mining (renewable-based or not) is currently insufficient to have a global-scale impact in the renewable energy sector.[59] However, were PoW mining to be adopted on a much larger scale, this significant impact could be achieved [43]. Some of the possible positive aftereffects of mining include:

Renewable penetration: PoW mining may enable grid mixes with a higher contribution from renewable sources than there would otherwise be, leading to a potentially decarbonizing effect. A few mechanisms can be credited with this:

Income effect: Both as a buyer of first and last resort, bitcoin mining may subsidize or incentivize renewable buildout (capacity expansion) on the margins [25], [67], [68]. A wide adoption of Bitcoin mining as a complement to VRE generation could provide a large-scale income source that is not only additional to energy sales, but also a stabilizing force: mining can do three of the five main demand-side management programs: peak-shaving, valley-filling and load-building [124].

Composition effect: Mining could allow finding two "golden chalices" of renewable energy markets, namely *net-decarbonizing additions of load* and *net cheapening additions of load*. The former refers to an increase in electricity demand that, counterintuitively, *reduces* the carbon emissions of the energy grid, by making low-carbon energy sources more profitable and displacing some high-carbon energy sources from the market. The latter refers to an increase in energy demand that reduces energy prices instead of raising them, because the upward pressure thereon introduced by the upward shift in the demand curve is more than counterbalanced by an upward shift in the supply curve, which itself is the result of an increased renewable supply due to a surge in profitability.

Both of these phenomena are regarded as conceivable [3], [73]. For instance, simulations by Lancium and IdeaSmiths, LLC estimate that CO2 emissions are reduced as a result of the introduction of highly flexible data centers (such as Bitcoin mining facilities) as a complement to grids with an overabundance of wind power, because it reduces the reliance on natural gas to balance out energy intermittency [87]. Instead of dispatching up generation (natural gas) in times of stress, the market may dispatch down load; as a result, an increase in energy consumption was more than offset through near-zero carbon energy (ibid).

Similarly, Nikzad and Mehregan expect a 77.7% reduction in the emission into the atmosphere of GHGs through the buildout of cogeneration projects of solar plants with cryptocurrency mining facilities [20]. Dogan et al [14] furthermore find that bitcoin clean energy and emission allowances are (Granger) causally associated with bitcoin, in both volume and price, whereas a bitcoin miner's revenues are negatively associated with carbon emissions (see also [125]). Similarly, Menati et al [73] conclude that miner-driven additions of load could reduce energy prices.

Transmission decongestion: Miners' portability (and scalability) means that they may be placed behind congested transmission nodes in the energy grid, further de-risking renewable buildout [67], [96].[60]

Grid resiliency and reliability: The large-scale adoption of renewable mining could act as a powerful ally to energy grids in terms of resiliency [73]. Grid resiliency is the adaptability of the grid to rapid fluctuations, quickly bouncing back from any disruptions to supply, demand, or transmission capacity [64], [68], [90], and is of high geopolitical importance [127]. A more "bitcoinized" grid would mean that there is an interruptible lever ("CLR") to regulate energy demand, which would allow reacting to all three (even "black swan" events [67]),[61] strengthening

[58]For instance, see the Sustainable Bitcoin Protocol: https://www.sustainablebtc.org/.

[59]Shan and Sun find that, although bitcoin mining can "stuff the belly" of the duck (curve), reducing the need for ramping capabilities, it cannot deal with the "neck" of the duck around sunset time in CAISO at its current scale [68, p. 7].

[60]Transmission/grid reinforcement, interconnection, and reserve capacities are expected to increase over time [70], [126], and hence node congestion might not constitute a permanent problem for grids [70]. Nevertheless, congestion management costs are increasing significantly at present [70].

[61]There are already cases of hashrate significantly dropping to allow for grid resiliency during winter storms [19].

grid resiliency [25], which is lower at high levels of renewable penetration [70]. The co-location of mining facilities with plants that are not flexible and can only produce a stable load equates to synthetically updating the plant for flexibility without changing the generation practices.

Transmission decongestion also provides a service in terms of resiliency.

Decarbonization through green hash rate: Mining may decarbonize not just by directly increasing the profitability of RE (and hence renewable penetration) but also by indirectly punishing high-carbon miners. If a miner is no longer located at the end user's side of a grid, and uses instead otherwise curtailed energy, this has an obvious net decarbonizing effect s[68]. However, even if *new* miners enter the market to use RE, this still decarbonizes *other* miners. New miners increase the hashrate, reducing the profitability of all other miners, including those on the end-user's side. This is an effect of the unique global zero-sum nature of the Bitcoin mining game. Therefore, either if existing mining infrastructure is switched to renewable sources or if additional ASICs enter the market on the renewable side, the carbon-intensity of mining is reduced.

Entrepreneurial and government error: Government promotion of renewable energies in the form of subsidies and quotas may have some benefits, but is also prone to exacerbate problems of entrepreneurial error and government error. The former happens by interfering with market signals such as prices or by delaying subsidies, which furthermore hampers "creative destruction" [128] and the discovery of the most efficient processes; the latter happens by engaging in the activity of "picking winners and losers" and by allocating funds without a market process to ascertain the efficiency of the expenditures themselves, which leads to capital misallocation. These issues were referred to by Ludwig von Mises [129] and Friedrich Hayek [130] as the calculation problem and the information or knowledge problem.

Bitcoin mining as a complement to renewable energy generation may ease these problems by introducing a market-based mechanism to subsidize renewable energies [67], while preserving price signals and the possibility of calculation. Mining may furthermore ease problems of capital allocation as a result of government action, e.g. by capitalizing on massively overbuilt hydroelectric capacity. Finally, because Bitcoin behaves like an "apex predator" of energy [131] it may force the discovery of the real value of electricity, and potentially even aid in finding a global market price for carbon, a long-sought environmental goal [42].

VII. Challenges of mining-based renewable penetration

We identify a series of obstacles for PoW mining-based decarbonization to succeed:

A. Difficulties in the market for PoW mining

In general, miners face bitcoin price volatility in the short [51], [111], [132] and long [69] terms, as well as production volume volatility [51].[62] However, price volatility may be hedged by shorting bitcoin futures and new hedging instruments are emerging to hedge production volume volatility such as difficulty derivatives, hash-rate derivatives and hash-rate tokens [51], in addition to the possibility to sell the hash rate [132] (with green hash rate being potentially sold at a premium). In addition, profit margins tend to be low and have even turned negative for many miners due to low bitcoin prices and unexpected increases in hashrate [91], [133].

Other issues include the supply of ASICs. The mining market has recently experienced supply chain bottlenecks with a semiconductor shortage reverberating downstream [11], [69], [134], [135]. Furthermore, the ASIC market structure is very concentrated, with Bitmain and MicroBT having a combined market share of approximately 80% [51]. Although this can be argued to be a temporary stage in the evolution of the market, and even an innovation-driving one (see VII-D), concentrated oligopolistic markets lead to restricted supply (on both economic and technical grounds), creating a time lag between bitcoin price increases and the entry of new mining capacity, limiting the ability to execute large-scale demand-response [51].

B. Internal competition between renewable mining subsectors

We established previously that high-uptime waste (landfill, stranded, flare) gas mining and low-uptime wind/solar mining take advantage of near-free (if not actually free or negatively-priced) energy that is otherwise very hard to exploit, if not for bitcoin mining's distinctive characteristics. As a result, these activities may be most efficient if undertaken with "outdated" ASICs that have been pushed out of the market through the hashrate increases produced by the entry of new mining capacity. This entails interactions between the two markets: an increase in one's profitability may signify a greater demand for common inputs, and hence a decrease in the other's profitability. These interactions remain under-researched to date.

C. Regulation and public outcry

PoW mining might not continue to exist at its current scale if the aforementioned "social license to operate" is revoked. PoW bans, which have been already imposed [3] and considered [28], [117] in many jurisdictions, pose thus a risk to the stability and sustainability of the market. The unpopularity of mining in given communities [51] may trigger further unfriendly regulation.

The favorability of regulatory interventions is not just a matter of banning or allowing, but also of the friendliness[63] of the regulation, its fine-tuning, and legal certainty[64] [3]. Miners

[62]Miners traditionally are not prone to hedge their investments, but rather to "be long," hold their proceeds [132], and even borrow against their BTC holdings, aggravating these circumstances.

[63]This does not completely exclude forms of decarbonizing regulatory *unfriendliness*. For instance, Roeck and Drennen [13] argue that miners should be *forced* to maintain a high renewable content to drive miners into greener areas ("carbon leakage").

[64]For instance, the abrupt removal of an electricity tax discount specifically for bitcoin miners in 2018 suddenly made mining almost entirely infeasible in Norway [51].

tend to move to Bitcoin-welcoming jurisdictions[65], but the continuity of a friendly environment remains always unknown. Note that fossil energy subsidies, which artificially undercut the ability of RES to sustain mining activity, should also be considered a part of the regulatory environment [16].

Naturally, regulatory friendliness may be endogenous in part, as a threatening political environment in combination with sufficient sector growth may lead to the emergence of advocacy and lobbying efforts.

D. Net negative impacts

Although it is possible that mining will lead to renewable buildout and hence *net decarbonizing additions of load*, it is also possible that it will create a demand for additional conventional energy, which would increase GHG [28], [30]). There have been isolated examples of this [11].[66] It is also conceivable for FTM mining to merely use up existing renewable capacity, displacing *other* consumers toward fossil energy,[67] despite miners' claims to be green due to the local grid mix (see theories of causality in II-B0b).

Projects that utilize otherwise curtailed solar and wind energy may furthermore mine with grid electricity in periods when it is profitable to do so [67], which on occasion may lead to positive GHG emissions as well. We consider all these issues in more depth in sections IX-C and IX.

E. Scale

In an electrified world, notwithstanding if Bitcoin's electricity consumption reached 1% of the global electricity consumption, this might be insufficient for significant worldwide decarbonization even if the arguments in favor of Bitcoin's "green" role are correct. On the other hand, this would mean that Bitcoin's electricity consumption would not manage to significantly aggravate climate change even if these arguments are wrong.

F. Long-term equilibria

While Bitcoin mining as a miner of first resort may stimulate RE buildout by providing a source of profits during interconnection queues, once electrification and decarbonization peak, those queues should progressively clear, meaning miners will have to consume from other sources.

[65]Mellerud [51, p. 60] lists the following as friendly jurisdictions: Japan, South Korea, the Netherlands, Portugal, Switzerland, Georgia, Malta and Singapore, as well as (...) Wyoming, Florida and Texas" in the US.

Specifically with regards to Texas, Mellerud [51] identifies a few key features of favorable market structure. First, deregulation, which entails few barriers, the existence of several electric providers competing for customers, and the ability for miners to negotiate directly with power plants without the need for an intermediary utility

[66]E.g. natural gas-based power plants that have been prevented from closing or re-ignited for bitcoin mining purposes [5], [13]. However, there is often more to these cases, e.g. when the mining facilities are enabling affording gas desulfurization equipment for the remediation of ash landfills from prior decades of coal mining activities [136]. Furthermore, some of these miners do purchase RECs, which in spite of their limitations do benefit the RE sector.

[67]Although BTM mining does not display this problem, it has challenges of its own, as life cycle assessments are harder to conduct outside of the grid, which leads to obscurity [13].

VIII. Alternative load resources

Bitcoin mining is not the only flexible, interruptible, portable, and potentially nonrival source of energy load that may supplement grid decarbonization. In this section, we survey other activities that may play some of these roles.

A. Water desalination

Water desalination is also a flexible, fully interruptible process that may be potentially supported with nonrival energy sources and act as a flexible load resource [67], [137]. Nevertheless, it is not as portable as Bitcoin mining as it requires pumping infrastructure, tanks and pumping scheduling systems [137]. Although some see desalination as a competitor to bitcoin mining [138], there exist also proposals for bitcoin mining and water desalination as complementary infrastructures [139], [140].

B. Water electrolysis for green hydrogen

Green hydrogen[68] production is also flexible, interruptible and potentially a good candidate for non-rival energy sources [67].[69] Hence, the green dream of a "hydrogen economy" [141] may even spur a competitor to bitcoin mining itself [21].

However, electrolysis can be argued to be more expensive than mining, requiring additional equipment and infrastructure for storage and transportation [21]. Electrolysis is also riskier and less lucrative [21] than mining,[70] as well as less flexible.[71] Finally, the output of electrolysis is also less portable and storable than bitcoin [3], [19], [51], [66], [107].

Electrolyzers are furthermore unlikely to replace miners as marginal load providers, especially in a hydrogen economy. This is because such a system would require an energy consumption level many multiple above mining's projected peak, which could not be met with curtailed energy but in a fraction [141]–[144]. The sheer scale of a hydrogen economy would additionally entail transportation costs, storage costs and internal competition issues.[72]

Overall, hydrogen and Bitcoin present different profiles. First, electrolysis is almost entirely dependent on a single variable: hydrogen price. In contrast, mining is dependent not just on bitcoin's price, but also on other variables such as difficulty, hashrate, CAPEX, etc. [21] Second, green hydrogen "specializes in seasonal demand flexibility", whereas Bitcoin mining is more suitable "for balancing unpredictable fast changes" [51, p. 9].

[68]"Grey" hydrogen is produced from natural gas, "blue" hydrogen is also produced from natural gas but carbon is recaptured and/or reused, and "green" hydrogen is renewable-energy based [21], [109].

[69]Lund et al point out that not just hydrogen, but also synthetic methane, may be produced with excess energy [81].

[70]Ghaebi et al furthermore note that there is a frequent error of overoptimism about excess (free) renewable energy in flexible hydrogen electrolysis projects [21].

[71]Ghaebi et al [21] note that electrolyzers are meant to run all year round to alleviate operation costs

[72]Between green hydrogen producers based on dedicated RES and with curtailed VRE, and between hydrogen and other RES.

C. CO2 removal

Carbon dioxide removal is also a potentially flexible and interruptible activity that could be powered with non-rival energy sources, [67] although its profitability is still unclear. A key differentiator between CO2 removal and mining is that CO2 removal is a public good subject to the tragedy of the commons, which could make it an imperfect candidate for load balancing in the absence of very significant subsidies.

D. Batteries

Batteries are a useful lever that is both flexible and interruptible [51], and can solve part of the daily intermittency problem by balancing load [11], [64], [67], [77]. However, and even if their price is expected to continue falling, [67] batteries are expensive and lower ROI in large scales [25], [64], [77] because of physical limitations to the ability to store energy without dissipation [11]. Moreover, they offer no additional benefit or profit other than flexibility itself [51], [77], unlike Bitcoin, and they offer a smaller energy sink.[73] Nevertheless, there is evidence to suggest that batteries may provide an efficient complement to Bitcoin mining in the "right mix" [3], [67]–[69], [77], [99], [100],[74] especially in the upcoming electrified world, where excess energy will be additionally useful [11]. Oeysti argues that "without bitcoin mining, renewables can provide only 40 percent of the grid's demand," but a combination of "bitcoin mining, batteries and solar can provide 99 percent of the grid's needs" [11, p. 40] (see also [67]).[75]

In this direction, consider that the energy consumption profiles of batteries are also different from miners': batteries only need energy for a few hours whereas miners may need it for longer periods. On the flip side, batteries can only supply energy for a limited time, whereas miners can technically be turned off indefinitely. This means that batteries are a better fit for some uses (e.g. on-site backup power) and bitcoin mining for others (e.g. sustained excess renewable energy over multiple days).

E. Other flexible data centers and CLRs

Non-time-sensitive computation is not exclusive to PoW mining. There is experimentation with the shifting of non-urgent computation tasks to match renewable generation peaks.[76]

Simulations have found flexible data centers to have indeed a net decarbonizing effect, as well as the effect to increase grid resiliency. Nevertheless, on both regards these centers are estimated to be inferior to cryptocurrency mining facilities [87] because of their comparatively lower flexibility [73] and efficiency [42].

F. Others

Other alternatives include other forms of DR programs, such as "sector coupling (power-to-gas, power-to-heat, and electric vehicles smart charging) (...) smart appliances in both commercial and residential buildings (...) industrial demand response (...) [and] load shedding schemes" [51, p. 10] (see also [21]). However, power-to-X solutions require "a meaningful probability of occurrence for low price hours to make it economically viable" [21, p. 5734], which limits their usefulness.

IX. Discussion

Throughout this article, we outlined the landscape of factors pertaining to Bitcoin's potential as a decarbonization tool. This allowed us to identify a few key areas for discussion.

A. Profitability and the problem of intermittency

Although bitcoin can be mined with VRE, the intense competition in the mining market raises the question of whether VRE-based operations will be profitable at all. The concern is that intermittent mining could be continuously outperformed by mining based on non-intermittent energy sources. Intermittency leads to lower uptime,[77] which entails longer time to recoup CAPEX, even under occasional negative energy prices conditions.[78] If, in turn, negative energy prices are very frequent, selling electricity to miners for free will not produce a significant benefit to a VRE project's profitability and could hardly be considered a subsidy to renewable buildout. A risk-averse individual may consider this to be further aggravated by bitcoin's long and short-term price volatility.

Indeed the problem of uptime versus intermittency is common to all potential VRE consumers, not just PoW miners. In the worst-case scenario, this issue would mean that mining is neither genuinely interruptible nor a non-rivalrous consumer. However, a few observations should be made:

Secondary power sources: Intermittently-powered miners often rely on a secondary, more expensive electricity supply to underclock for in the absence of VRE [76]. The combination of both may lead to a competitive Levelized Cost of Energy (LCOE).[79]

Low CAPEX miners: Cheaper, older ASICs are less reliable and efficient, hence trading at a discount.

[73]ESG concerns related to lithium set aside.

[74]Eid et al [77] find batteries to be inferior to bitcoin mining in terms of ROI, but the combination of both to be a superior alternative to either activity in isolation, because of increases in profitability and optimizations to the batteries' "state of charge."

Frumkin [69] also notes that batteries, just like non-intermittent secondary energy sources, allow increasing uptime when it is not enough to break even on the mining CAPEX

[75]This is compatible with the IEA's projection that "to meet four-times the amount of hour-to-hour flexibility needs, batteries and DR step up to become the primary sources of flexibility" [86, p. 177].

[76]Such as uploading YouTube videos or adding new words to Google Translate [145]. Note however that Google is a leader in its sector but this is not the norm among the data center industry [146].

[77]Additionally, intermittency entails thermal cycling, which accelerated the degradation of silicon chip quality. However, there is little data on the extent to which this is a factor [76].

[78]Currently, even extremely cheap electricity prices are not enough to make most operations viable with less than 60% uptime [69].

[79]The LCOE is the result of dividing the lifetime cost of building and operating a power generation asset by the kWh of energy that it produces [69]. LCOE is not an all-encompassing metrics, however, as it disregards system integration costs (costs of managing variability and uncertainty of energy output, e.g. by operating reserve and back up plants), which increase with VRE penetration, hampering its political feasibility [70].

As a result, their profitability depends comparatively more on OPEX than on uptime. Although indeed even a low CAPEX ASIC is more profitable mining 24/7 than intermittently at the same electricity price, electricity prices are not constant, and this different profitability profile means that less efficient ASICs are more sensitive to electricity prices, potentially being more profitable under intermittent patterns.

Vertical integration: Although selling negatively priced or near-zero electricity to a miner indeed does not add much to a generator's profitability, this does become the case when the miner and the generator are the same party. At low CAPEX, this possibility may not come at the cost of much additional investment.

Additionally, if indeed 24/7 generation offers a substantial advantage over intermittent generation for mining, this may still pose a decarbonizing effect. Flare mining is a form of non-intermittent mining with a substantial decarbonizing effect,and it is nevertheless unclear that it would consistently outperform VRE mining. As it faces higher CAPEX, such as generators, together with scalability obstacles, flare mining may progressively slide toward higher-efficiency miners, not competing with VRE mining. It is conceivable that coal plants may stay at minimum generation levels during negative price periods, but this entails additional OPEX (fuel) in comparison to VRE mining. Finally, hydro mining (which eases an important capital misallocation issue in an environmentally friendly manner) faces important limits to growth in the long run, as hydroelectricity is not expected to grow as much as VRE [147].

Ultimately, it is not impossible (though it is indeed unlikely, see IX-C) that the profit asymmetry between flexible mining with low-efficiency (and low-cost) rigs and uninterrupted mining with high-efficiency (and high-cost) rigs is so large that the former model is completely unprofitable. However, if the efficiency of newer rigs were indeed so high, this would depress the energy consumption of the Bitcoin network, mitigating the environmental concerns as well.

B. Fairness of criticism and framing

All the opportunities discussed in this paper do not manage to *guarantee* that *every* addition of load will be carbon-neutral, or of the extremely flexible kind. It is also challenging to provide hard assurances concerning decarbonization timeframes. Similarly, the expectation that Bitcoin's energy consumption will eventually stop climbing and stabilize [3], [51] is plausible, but not guaranteed. On the other hand, these requirements may be argued to be excessive, as no other industry is subjected to such extreme impositions. When data centers contract renewable energy (e.g. Google's [148]), they are not usually criticized for consuming electricity that could have been destined for other uses.

It should also be noted that requiring new additions of load to be carbon-neutral presumes a particular theory of causality based on incumbency (see II-B0b), which to attribute impact to the "marginal load" may equivocate proximate causes and ultimate causes, assume a negative value judgment about Bitcoin, implicitly presuppose that older bidders of electricity have a more legitimate claim to the green share of electricity than younger ones (which needs to be justified), or incur in double-counting (attributing emissions to the marginal load and the incumbent load simultaneously). Regardless, the criticism that mining leads to an additional marginal load should also be accompanied by the admission that mining leads to an additional marginal revenue for RE producers by increasing energy demand, which is often not the case.

Overall, Bitcoin should be subjected to reasonable requirements. A location-agnostic buyer of last resort that can protect a downside case in financial models and purchases otherwise-curtailed energy need not purchase exclusively VRE energy insofar it does not consume under peak demand and price conditions (which would incentivise fossile capacity expansion).

C. Second-order game theory: A trend towards a perfect competition environment?

It is plausible to expect mining-based additional loads to stimulate renewable buildout. A key factor in this regard is that bitcoin mining not only displays a near-perfect competition environment, but also is very likely to slide even further toward perfect competition over time. Perfect competition entails marginal cost sensitivity, which as established favors complementing VRE generation. We now explore these claims:

a) Mining is already close to perfect competition in the present day: Mining produces an entirely homogeneous product, namely bitcoin, which is secured through strong property rights [3], and can be traded at near-zero transaction costs through technologies such as the Lightning Network. Although there are still some imperfections in the dissemination of market information, it displays an increasingly large number of buyers and sellers. Furthermore, there are non-increasing returns to scale (in fact, scale may have decreasing returns if fear of a 51% attack is triggered), there are little barriers to entry (apart from the time to get a grid connection) or exit and there is near-perfect factor mobility (as shown by the China ban experience and seasonal pre-ban migrations within China [3], [19], [48]). Empirically, the Bitcoin network also seems to follow the Pareto Principle or 80/20 rule, in another indication that it approximates a perfect competition state [19] (see also [11]). The main differentiator is generally the cost of energy.

b) Mining's tendency toward perfect competition is posed to exacerbate: This is a result of a series of factors:

Increases in difficulty: They are a result of the increasing hash rate and drive down profitability, meaning that only the miners with lower electricity costs are able to survive the upward adjustments [69]. Difficulty is expected to continue rising rapidly for the next years, in a clear trend for the average cost of mining a BTC to equal BTC price [69].

The effect of halving: Every four years, block rewards are cut in half, which along with difficulty adjustments pushes miners to the lowest possible input costs, especially to survive BTC-USD bear markets [3],

[122]. A fixed BTC supply, together with halving, additionally reduces the profitability of mining.

The expected clearance in the ASIC supply chain: In recent years, the bitcoin bull market coincided with a bottleneck in the production of ASICs. This is however clearing and expected to continue clearing over time [134] (see also [135]).

Commodification of mining equipment: Although we established that the ASIC production market is currently highly concentrated, there is an extended expectation that mining equipment will commodity, especially with the decreasing rate of efficiency increases (see below). This is expected to drive CAPEX further down, with prices following production costs rather than bitcoin prices [11], [19].

Decreasing rate of increases in rig efficiency: Hashrate increases reduce the profitability (and increase the cost-sensitivity) of mining, but rig efficiency increases counterbalance this. A necessary condition for Bitcoin to become a true flexible demand sink is a slowdown in efficiency increases.

Since the beginning of the ASIC mining era (2013), rig efficiency has been periodically improving by orders of magnitude. However, this is slowing down significantly [76]. Efficiency increases due to hardware miniaturization fall as quantum limits (and hence, increasing error rates) are approached. A lower rate of hash rate increases entails higher ASIC life time, which raises the supply and the price-sensitivity of the hashrate. This reduces the marginal revenue of mining, which simultaneously limits total hashrate growth and exacerbates cost-sensitivity, entailing in turn a higher tolerance of downtime (intermittency) and hence additional suitability of mining for load balancing.

Note also that, as the hardware playing field levels, competitive advantages are decreasingly obtained through purchases of newer rigs, and increasingly through more sophisticated PPAs and by mining-VRE co-location [76].

Increasing access to credit: As the mining industry matures, there is a plausible argument that miners will get increasing (credit ratings and) access to credit to underwrite new renewable buildout. This is realistic as other data centers have already done this, including mining facilities.[80]

Limits to the ability of bitcoin's price to increase: Together with rig efficiency increases, the other factor increasing mining profitability and reducing cost-sensitivity is bitcoin price increases. The more BTC price grows, the lower the decarbonizing effect of the other trends identified in this article. However, BTC price cannot grow indefinitely in an exponential manner, meaning that as the digital asset achieves mainstream adoption and its price stabilizes, its suitability for load balancing will increase. Mellerud estimates that "in the long-term, Bitcoin's energy consumption will only continue to climb if the bitcoin price more than doubles every four years" [51, p. 61]. Alternatively, miners would have to reduce the cost of IT by 50% every 4 years, but even if CAPEX can come down (increasing the weight of OPEX), it cannot halve repeatedly.

The combination of these trends strongly suggests that miners' marginal cost will trend toward equalling their marginal income, and hence that the incentive to operate flexibly will significantly increase over time. In this context, it is reasonable to expect only or mostly near-free, free, or negatively-priced energy sources to lead to economic profits, and for miners to be encouraged to contract with newly-built wind and solar plants, meaning that a highly renewable scenario is more plausible with a large-scale mining scenario than otherwise. [66]

There is a strong expectation for bitcoin mining is going to become ultra-competitive in a relatively short term [76], with many miners going bankrupt in a bear market and selling their assets to other miners with lower energy prices – all leading to a strong push for efficiency in a zero-sum game.

D. The short and the long run

We observe that much of the disagreement regarding Bitcoin's potential for decarbonization seems to relate to how long the view that the proponent is willing to take is. A very immediate concern calling for immediate emergency degrowth in energy consumption requires a negative evaluation of Bitcoin's energy consumption. In turn, the expectation of Bitcoin to run only on BTM intermittent RES in a decade or two, but not entirely doing so in the interim, may lead to friendly perspectives on this digital network.

Bitcoin's projected energy consumption may be seen as a huge proportion of RE generation if only the next few years are considered, but not if an additional decade is allowed for. In a similar direction, Imran [42, p. 12] expects miners to act in an arbitrageur manner, first targeting "areas of energy surplus such as China, Canada, Norway [and] Iceland" and later moving into the renewable sector, looking for near-zero or even negative costs (see also [19]).

E. Takeaways

Bitcoin mining[81] displays a promising, though not yet entirely confirmed, potential to support renewable energy penetration. This is relevant as it shows a tool that may be of aid toward grid decarbonization.

Bitcoin mining is drawn to inexpensive sites for power sources. Although these may be carbon-intense sites, there is evidence to suggest that VRE sources are preferred and that

[80]See Aspen Creek Digital, https://acdigitalcorp.com/.

[81]Our results are focused on Bitcoin but apply to other PoW blockchains as well ([149]). Nevertheless, the reader should consider the difficulty of not only multiplying Bitcoin's current scale several times, but also competing PoW DLTs simultaneously matching this scale

this trend will strengthen.[82]. Among renewable sources, while individual sites such as hydro or geothermal will continue to exist, solar and wind are gaining importance, given a cost and scalability advantage [11], [67].[83]

Nevertheless, the argument that Bitcoin leads to decarbonization cannot be grounded just on Bitcoin being drawn to VRE sources. For decarbonization, mining should also constitute a flexible load *that does not add to peak demand*. With mining currently require a high uptime, this is not fully the case in the present day [76].

Overall, and in spite of concerns about PoW energy consumption, we have found a significant body of work suggesting that mining may be a powerful tool toward decarbonization. Further research in this direction (see IX-F) is thus required and encouraged. We moreover advise regulatory interventions to be formulated with extreme care, "as outright bans, punitive taxation or overly burdensome regulation" maybe have "the exact opposite of the desired effect by driving miners further into the jurisdictions where fossil fuels are heavily subsidized, thereby increasing emissions" [16, p. 18].

Bitcoin mining for demand-response services is already a growing sector [51]. This is not to say that there are no challenges, and several have been identified (see VII). On a positive note, however, Vazquez and Crumbley [111] point out that all the advantages of bitcoin mining (e.g. interruptibility, flexibility, portability, etc.) are intrinsic *technical* strengths. Instead, the disadvantages are mostly economic factors and contingent technical circumstances. An additional key advantage of Bitcoin miners is that they need minimal policy support (e.g. subsidies) to deploy themselves to supply renewable buildout.

F. Future work

With the entire sector being under-researched, many avenues for future research show promise. These include the exploration of specific business models for renewable-based mining, case studies showing profitability or the lack thereof empirically [91], scalability studies, ascertainment of the best geographic (and regulatory) locations for mining, the quantification of Bitcoin's positive and negative externalities, and more.

To guide public policy, we especially encourage rigorous end-to-end carbon accounting projects in the various renewable-based bitcoin mining niches, as well as, following Dogan [14, p. 12], the investigation of the contribution of PoW-based cryptocurrencies "in determining the trade-off between renewable and non-renewable energy consumption," as well as the existence of potential non-linearities in this regard.

G. Limitations

This paper has not considered in depth other environmental impacts that go beyond GHG emissions, notably the impact of bitcoin mining in acidification, particulate emissions and smog formation, which have already been identified as areas for future research by others [13]. Additionally, some areas of environmental impact have been considered superficially (e.g. e-waste and noise pollution).

Furthermore, the reader should consider that this paper is not exhaustive of all the issues framing this discussion. For instance, an understanding of the explanation of bitcoin mining, Bitcoin's value and Bitcoin's value proposition are assumed and outside of the scope of this paper. Similarly, the 1.5 degree goal is taken as a standard reference framing the climate change debate and not necessarily advocated for [150].

Finally, there are some obvious limitations that should also be taken into account. Most notably, research on the environmental impact of Bitcoin (even on Bitcoin itself) and especially on its impact on renewable energies is both still embryonic and fast-paced, meaning that significant findings may emerge after the release of this paper. This article also makes some elementary assumptions that are plausible but nonetheless contingent, such as that in the short run PoW-based cryptocurrencies will not entirely cease to exist.

H. Conclusion

Bitcoin is indeed a network displaying a high electricity consumption. Nevertheless, this does not necessarily entail an equally high carbon footprint that is permanently sustained. There is evidence to suggest that bitcoin miners are unique energy buyers that may make bitcoin mining a flexible load resource for ancillary services provision. This has the potential for a net decarbonizing effect.

In this direction, it is not obvious that mining will necessarily be hyper-flexible. It is clear that Bitcoin-based decarbonization requires lower ASIC utilization rates than the present day (and a higher relevance of electricity among total expenses), but advocating for Bitcoin-based decarbonization requires allowing for paths to net-zero that are not necessarily in a straight line.

Although flexible loads may be instrumental in the fight against climate change, their usefulness naturally depends on the load's willingness to be flexible. However, we observe a trend of the break-even value of miners going to zero, of renewable penetration (and, thus, curtailment) increasing, and even of bitcoin price volatility falling in the long run. This all suggests that Bitcoin may indeed be willing to be as flexible as decarbonization requires.

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Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

[82]Additionally, general decarbonization efforts will positively impact Bitcoin's carbon-intensity profile insofar as it relies upon "the grid" [3], [19]

[83]The BCEI [67, p. 2] believes this to be especially true "for solar, a semiconductor technology, which has consistently declined in price by 20-40%3 per doubling of cumulative capacity deployed."

Acronyms

ASIC application-specific integrated circuit
BECI Bitcoin Energy Consumption Index
BMC Bitcoin Mining Council
BTC Bitcoin Core
BTM behind-the-meter
CLR controllable load resource
CO2 carbon dioxide
DLT distributed ledger technology
DR demand-response
ETFs exchange-traded funds
EU European Union
FTM front-of-the-meter
GHG greenhouse gas
GOs guarantees of origin
GWP global warming potential
IEA International Energy Agency
IPCC Intergovernmental Panel on Climate Change
L1 layer-1
L2 layer-2
LCOE Levelized Cost of Energy
NCLR non-controllable load resource
OSTP Office of Science and Technology Policy
PoS proof-of-stake
PoW proof-of-work
PPA power purchase agreement
RE renewable energy
RECs Renewable energy certificates
RES renewable energy sources
ROI return on investment
US United States
VOCs volatile organic compounds
VRE variable renewable energy

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