Drivers of Bitcoin Energy Use and Emissions

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Abstract. The global Bitcoin mining industry has grown to a size where its overall energy consumption is frequently compared to that of entire countries. Indeed, as of 30 April 2022, following the successful migration of the entire Chinese mining industry after its expulsion from China in mid-2021, Bitcoin uses approximately 247.0 TWh of primary energy per year, slightly less than the entire nation of New Zealand, the 63^{rd} ranked nation by total energy consumption. To understand what drives Bitcoin's energy use and emissions however, one must understand four key concepts: how Bitcoin works and incentivises its miners, the nature of competition in the mining industry, the nature of mining hardware and innovation, and importantly, international energy and electricity markets and the differences between them. This paper will provide a thorough explanation of these concepts, as well as provide commentary on Bitcoin's current state, and what the Bitcoin Mining Industry may potentially look like towards the end of the decade.

Keywords: Bitcoin · Energy · Emissions · Perfect Competition

1 How Bitcoin Works and Incentivises Its Miners

Bitcoin's creators hypothesised that "*a purely peer-to-peer version of electronic cash would allow online payments to be sent directly from one party to another without going through a financial institution.*" [1] To achieve this, a peer-to-peer network with a timestamped, append-only, distributed ledger, commonly known as The Blockchain, was proposed. To keep all actors honest, miners are required to expend computational energy to earn the right to add the next block of transactions to The Blockchain, and the associated economic rewards that come with it.

To oversimplify an extremely technical process, Bitcoin mining is effectively guessing a number, "hashing" it with a universally agreed upon algorithm, and hoping that you are the first to guess correctly. You can think of performing a single hash as scratching a single lottery ticket. You can perform a hash by hand, however, modern mining rigs undertake several trillion hashes per second (TH/s), or, to continue the analogy, scratch trillions of lottery tickets per second.

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All tickets are identical, save their unique serial number. The more tickets you scratch, the higher the chance of winning the lottery. If you control 10% of the network hash power, you could expect that, on average, you will earn 10% of block rewards. It takes energy to scratch the ticket. If you have the right number, but a bad ticket (i.e. you are trying to behave dishonestly), all your effort scratching tickets goes to waste. At any moment in time, on average, the network is only ten minutes away from the next correct guess. Every two weeks, or more precisely 2016 blocks, the Bitcoin network checks to see if a ten minute average cadence was achieved. If the correct guesses occur too frequently, the set of numbers to guess from, or, "the difficulty" increases to bring the frequency back to ten minutes. If the correct guesses are too infrequent, the difficulty is reduced, and the pool of numbers to guess from decreases. This defining feature of Bitcoin, known as "The Difficulty Adjustment" guarantees the stability of the predetermined issuance schedule [2].

People invest energy into Bitcoin because they are incentivised to do so. As long as the cost to mine is lower than the market price of bitcoin, the incentive exists. When it comes to energy expended by miners, the incentives can be broken into two broad categories; endogenous incentives, i.e., the economic incentives built into the Bitcoin Protocol, and exogenous incentives, i.e., the entrepreneurial instinct to remain alive amid extreme competitive pressures.

1.1 Endogenous Incentives

Bitcoin primarily incentivises its miners with the block reward, which consists of the predetermined supply issuance for the successful mining of a block (or, "block subsidy"), plus, all transaction fees associated with that block [3]. During Bitcoin's bootstrapping, miner income was heavily skewed towards the block subsidy, with the initial subsidy being 50 bitcoin per block. With the block subsidy halving every 210,000 blocks, or, roughly 4 years, miners will eventually be compensated strictly by transaction fees [4]. The block subsidy is currently 6.25 bitcoin per block, with transaction fees now becoming a larger percentage of miner income. Importantly, bitcoin mining uses application-specific hardware which can only be used for mining bitcoin (alongside a few other SHA256-based micro-cap altcoins and Bitcoin forks) [5], so any attacker who amasses the necessary hardware and energy to control more than 51% of the network should rationally be more incentivised to earn 51% of the block reward, rather "*than to undermine the system and the validity of his own wealth.*" [1]

1.2 Exogenous Incentives

As mentioned previously, the specificity of the infrastructure required by miners incentivises them to make sure Bitcoin prospers, otherwise, the billions of dollars spent on Bitcoin mining rigs and energy infrastructure will be near worthless. That said, the more that Bitcoin prospers, the more incentives miners have to capture profit, which typically means more competition and pressure to stay alive. Miners are thus incentivised to continue expanding and improving their operations to maintain their share of the network computing power, or "Hashrate." [6] The circularity of the incentives make them robust and self-reinforcing.

2 The Nature of Competition in the Bitcoin Mining Industry

2.1 Perfect Competition

The example of "the hypothetical firm in a perfectly competitive market" is taught in most introductory economics classes. A literature review of primary academic texts identifies eight conditions that define a perfectly competitive market, as shown in the table below [7–12]. The following subsections will provide a point-by-point demonstration of how Bitcoin mining is a near-perfectly competitive market, and what this typically means for industry competitors (Table 1).

Table 1. Conditions of a Perfectly-Competitive Market

Homogeneous Products	Perfect Factor Mobility	Zero Transaction Costs
Non-increasing Returns to Scale	Guaranteed Property Rights	Perfect Information
No Barriers to Entry or Exit	Many Buyers and Sellers	

Homogeneous Products, Guaranteed Property Rights and Zero Transaction Costs. Bitcoin's digital signature algorithm, combined with proof-of-work mining, guarantee ownership rights. Bitcoins are simply entries in a global ledger, and are entirely homogeneous and fungible. Whilst Bitcoin transaction costs are not zero and never will be, transactions on Bitcoin's second (and higher) layers, such as the Lightning Network [14], will eventually approach zero for most end-users. It is possible to store bitcoins indefinitely at zero cost, i.e., one could simply remember a seed phrase, a list of words that contains all the information you need to access and spend your funds [13]. All three criteria are currently met by Bitcoin.

Perfect Information and Many Buyers and Sellers. In research from July 2021, leading cryptocurrency exchange Crypto.com estimated that there were 176 million Bitcoin users globally in January 2022, up from 113 million in June 2021 [15]. Whilst this is a large number, there is no explicit definition of "many" laid out in the literature, and compared to the user-bases of tech giants such as Facebook, Netflix and YouTube, an argument could be made that 176 million users are not that many. Further, the high volatility still experienced in Bitcoin indicates imperfections in the proliferation, or even creation of, market information. That said, if the user-base grows into the billions over the coming decades in a similar way to the tech giants' user-bases, both of these criteria will be met.

Non-increasing Returns to Scale. When one dishonest entity controls more than 51% of the network hashrate, they can potentially double-spend their own funds, and prevent others from transacting on the network, effectively destroying the value proposition of Bitcoin [34]. Bitcoin has never been openly 51%-attacked, and likely never will be due to both cost and physical semiconductor industry limitations. That said, in 2014, a popular cloud mining platform, GHash.io managed to attract over 51% of the hashrate to their pool, in what was described by the media as a "doomsday scenario" [16]. What quickly ensued was mass user panic and migration away, and within a few months, GHash.io ceased to exist. Not only can returns stop scaling, but excessive growth can put you out of business.

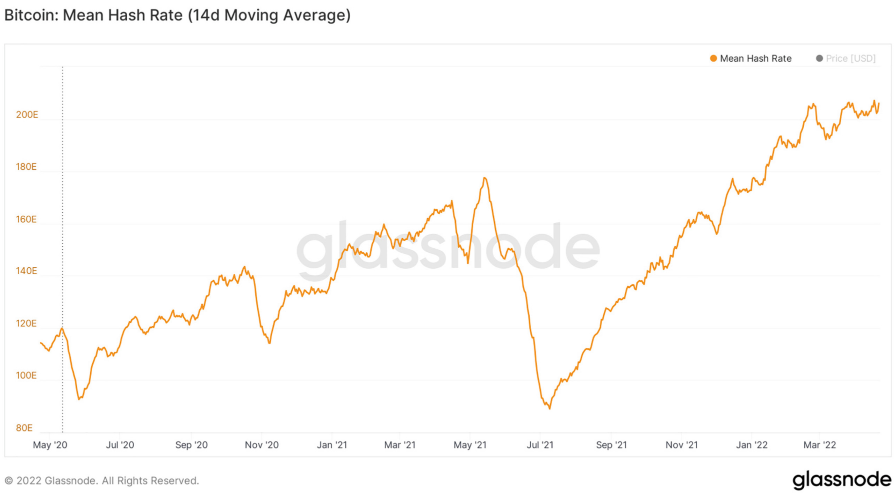

Fig. 1. Bitcoin Mean Hash Rate (14-day Moving Average), April 2020 - April 2022. Dotted vertical line indicates Block Reward Halving in May 2020 [19].

No Barriers to Entry or Exit and Perfect Factor Mobility. The mobility of Bitcoin's factors of production has thus far been best publicly demonstrated by the Chinese mining industry. This can be observed in Fig. 1, where throughout 2020, prior to being expelled from the country in mid-2021, "*miners within China were staying mostly in the more stable coal-fired regions like Xinjiang in late autumn, winter and spring ('dry season'), and migrated to regions with significant temporary overcapacities in low-cost hydropower, like Sichuan, between May and October during the 'wet season'.*" [17] Here, we see between 20 to 25% of the network hashrate successfully relocate within a matter of weeks. The more obvious and extreme example in Fig. 1 is the expulsion of miners from China in late-May 2021, resulting in a 50% reduction in the 14-day average hashrate from an all-time-high 177.5 exahashes per second (EH/s) on 13 May 2021 to 89.0

EH/s on 9 July 2021. After one month however, over 25% of the hashrate was back online, after 3 months, the majority, almost two-thirds, had returned, and just under 6 months later, on 2 January 2022, an all-time high 14-day average hashrate of 177.5 EH/s was reached. To be sure, deployment of brand new equipment accounts for some of this hashrate increase, however, due to the ongoing global semiconductor shortage and broader COVID-related supply chain issues, it is not a major contributor [18]. Although truly "perfect" factor mobility would require teleportation, the speed and relative ease at which the bitcoin network recovers from major shocks demonstrates very high factor mobility and limited barriers to entry or exit.

2.2 Characteristics of a Perfectly Competitive Market

Economic profit tends to zero in long-term equilibrium in a perfectly competitive market, and the marginal cost of producing and the market price oscillate around an equilibrium point [7]. Therefore, so long as the price of bitcoin is greater than the cost to mine it, competition will enter the market to close the gap, and vice versa. In such competitive markets, there is also a natural tendency for the market to be dominated by three or four players [20,22]. The Pareto Principle, also known as the 80/20 rule, states 20% of the market participants will tend to control 80% of the market [23]. In terms of Bitcoin's mining pools, the top six collectively control 77.2% of the total hashrate, with the biggest pool, Foundry Digital, controlling 19.2% of hashrate, and ViaBTC, the sixth biggest, controlling 9.7% [24]. As will be discussed in the next sections, the only way to stay in business in such an environment is through cost and/or innovation leadership [25].

Cost Leadership. There are two main routes to cost leadership; having the lowest capital expenditure (CAPEX) per unit of hashing and/or having the lowest operating expenditure (OPEX) per unit of hashing. For the former, this may involve a miner fabricating their own ASIC hardware to save on the fabricator's margin, or developing favourable relationships with ASIC manufacturers, infrastructure providers and other partners throughout the capital expenditure supply chain. In terms of OPEX, cost leadership could mean finding cheaper power and hosting facilities than your competitors, or tailoring your energy inputs and datacenter model to the type of hardware you deploy [40]. Miners are not necessarily environmentalists, however, the cheapest power in the world is increasingly becoming renewable [59].

Innovation Leadership. Innovation leadership relates to doing things better than your competitors rather than cheaper. The two broad areas that Bitcoin miners can innovate within are their technological capabilities and managerial approach.

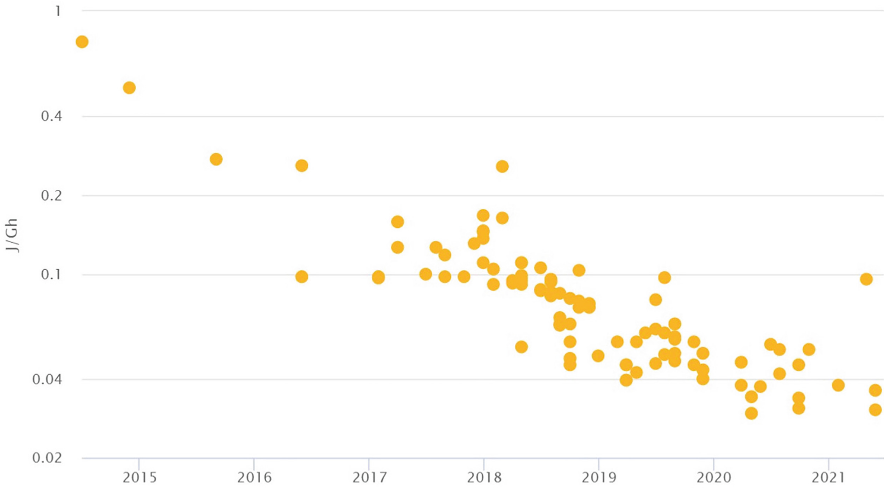

Fig. 2. Evolution of Bitcoin Mining Equipment Efficiency (2014–2021) [27].

Technological Innovation. Ever since Application-Specific Integrated Circuits (ASICs) became the dominant computing force behind Bitcoin Mining in late 2013, improvements in hashing power per unit of energy have improved at a steady, yet dramatic pace [26]. Figure 2 shows the evolution of Bitcoin mining equipment efficiency, measured in joules or Watts per gigahash (W/GH). Efficiency has improved from 0.77 W/GH in July 2014 (Bitmain Antminer S3) to 0.04 W/GH in June 2021 (Bitmain Antminer S19j), a reduction of almost 95%. As of this writing, the currently sold Bitmain Antminer S19 Pro has improved a further 26% to 0.0295 W/GH, with Bitmain's next model to be shipped in July 2022, the S19XP, boasting an additional improvement of 27% to 0.0215 W/GH [29]. This consistent improvement, coupled with the profit motive, has driven exponential growth in network hash rate over the past 8 years, as shown in Fig. 3. Although the ramifications of the global semiconductor shortage will impact procurement of new hardware in the short-to-medium term, it will not slow the pace of innovation.

Those miners not fabricating their own hardware can still innovate in areas such as datacentre cooling and configuration. Publicly listed Bitcoin miners, such as Riot Blockchain, are now investing in liquid immersion cooling to increase reliability, equipment lifetime, and reduce energy needed for cooling [43]. Importantly, immersion allows miners to reduce capital expenditure per unit of hashing due to the ability to dramatically overclock the mining equipment safely [43]. In terms of datacentre layout innovation, there are also publicly listed Bitcoin mining companies, such as Mawson Infrastructure Group, who deploy modularised or shipping-container-based solutions, which allows them to take their operations anywhere on Earth, land or sea, with a reliable power source and internet connection [44]. This modularity is already having a real-world impact, which will be discussed further in Sect. 3.

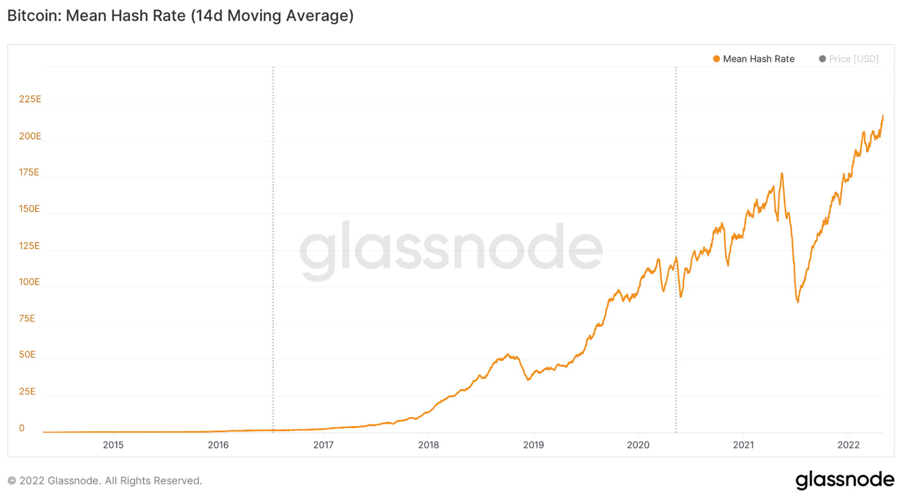

Fig. 3. Bitcoin Mean Hash Rate (14-day Moving Average), April 2014–April 2022. Dotted vertical lines indicate Block Reward Halvings [19]

Managerial Innovation. Whilst not as easy to measure as improvements in cost or energy per hashing unit, innovation in management and entrepreneurial techniques can make or break a business. For example, large Chinese miners who had robust risk management and business continuity plans in place in the face of increasingly hostile legislation, were able to relocate their operations with speed and minimal disruption and financial loss. Financially innovative and publicly listed miners also have the benefit of access to capital markets for funding to take advantage of or damp market shocks. Finally, innovation in procurement through industry partnerships can also provide a competitive edge.

3 International Energy and Electricity Markets

3.1 Energy and Emissions

Although energy and emissions are closely related, the terms are frequently conflated. Using more energy does not necessarily mean more emissions. The use of energy has allowed our civilisation to prosper, and future prosperity will depend on our ability to produce more energy at a lower environmental cost. The amount of greenhouse gas emissions (GHGs) per unit of energy, sometimes referred to as carbon or emissions intensity, differs dramatically across different energy sources and geographical locations, as will be discussed in detail in the next section.

Carbon Intensity. The International Panel on Climate Change (IPCC) published figures on the carbon, or emissions, intensity of different electricity generation technologies, based on a literature review of almost 300 Life-cycle analyses, as summarised in Fig. 4. At the 50^{th}-percentile, the results show that renewables, nuclear and hydropower are dramatically cleaner than fossil fuels. However, looking at the extremes paints a different picture. For example, the world's best Carbon Capture and Storage (CCS) Coal facilities, which emit 98 g of CO_2eq/kWh, are comparable to the 75^{th}-percentile Solar-PV installations at 80 g, and less than half the carbon intensity of the worst-in-class Solar-PV installations. In fact, the worst-in-class Natural Gas CCS plant was still comparable to the worst-in-class Solar-PV plant, the former emitting 245 g compared to Solar-PV's 217 g.

Table A.II.4 | Aggregated results of literature review of LCAs of GHG emissions from electricity generation technologies as displayed in Figure 9.8 (g CO_2eq/kWh).

Values	Bio-power	Solar		Geothermal Energy	Hydropower	Ocean Energy	Wind Energy	Nuclear Energy	Natural Gas	Oil	Coal
		PV	CSP								
Minimum	-633	5	7	6	0	2	2	1	290	510	675
25th percentile	360	29	14	20	3	6	8	8	422	722	877
50th percentile	18	46	22	45	4	8	12	16	469	840	1001
75th percentile	37	80	32	57	7	9	20	45	548	907	1130
Maximum	75	217	89	79	43	23	81	220	930	1170	1689
CCS min	-1368								65		98
CCS max	-594								245		396

Note: CCS = Carbon capture and storage, PV = Photovoltaic, CSP = Concentrating solar power.

Fig. 4. Aggregated results of literature review of LCAs of GHG emissions from electricity generation technologies (g CO_2eq/kWh) [30].

The recent Chinese ban on mining has helped shift bitcoin mining away from worst-in-class non-CCS Chinese coal plants towards best-in-class Natural Gas in the USA and other cleaner sources of energy around the world, helping Bitcoin dramatically reduce its carbon intensity. This migration and Bitcoin's carbon intensity will be discussed in more detail in Sect. 4.

For context, based on the 50^{th}-percentile figures shown in Fig. 4, the carbon intensity of the world's energy production in 2020 was 622.7 g CO_2eq/kWh [53], and 487.12 g for the world's electricity production [54]. Data from the International Energy Agency (IEA) in 2018 showed an electrical grid intensity of 476 g CO_2eq/kWh as a global average, 709 g in India, 613 g in China, 571 g in Southeast Asia, 405 g in The USA, and 269 g in The EU [55].

Greenhouse Gases (GHGs) and Carbon Dioxide. While not as dangerous a conflation as energy, electricity and emissions, we again arrive at a similar position: whilst carbon dioxide is a GHG, not all GHGs are carbon dioxide. In fact, only 65% of GHGs come from CO_2 from fossil fuel and industrial processes, 11% from CO_2 from forestry and land use, 16% from methane, 6% from nitrous oxide, and 2% from F-gases [31]. In terms of warming potential, over a 20 year period, methane is 56-times more potent than CO_2, nitrous oxide is 280-times more potent, and F-gases are hundreds to thousands of times more potent, with sulfur hexafluoride, for example, having 16,300-times more global warming potential than CO_2 over 20 years [33]. This is why carbon intensity metrics are measured in "CO_2 and CO_2-equivalents". For example if a certain activity emitted 1 g of methane, it will have emitted 56 g of CO_2-equivalents. In total, 49,360 megatonnes (MT) of GHGs were emitted globally in 2016 [52], of which CO_2 made up only 35,200 MT [51].

In 2019, 150 billion cubic metres of methane were flared around the world as part of routine oil and gas industry operations, equivalent to around 1,500 terrawatt-hours (TWh) of energy, or, enough to power Bitcoin almost 15 times over [32]. Bitcoin miners will play a practical, profitable and pivotal role in methane flare mitigation, which is discussed further in the next section.

3.2 Energy and Electricity

Energy and electricity are often conflated but are strictly distinct. Whilst all electricity is energy, not all energy is electrical. Based on data by The University of Oxford's Our World in Data (OWID) project, of the approximately 173,000 TWh of primary energy produced in 2020 [35], less than 15%, or roughly 26,000 TWh was electrical energy [36]. Further, similar to the hundreds of millions of people around the world surviving without an electrical grid [37], Bitcoin does not need an electrical grid, only an energy source. The next sections provide a summary of how Bitcoin is currently capturing and using both energy and electricity in innovative, profitable, and importantly, sustainable ways [40].

Converting Energy into Electricity. All electricity starts off as raw, primary energy, be it oil, gas, wind or sunlight, and a proportion of this can be converted to electrical energy. Natural Gas has a conversion factor of 44%, meaning that 0.44 kWh of electricity is generated for every 1 kWh of raw energy input [41]. Conversion factors for coal and nuclear are similar at 32% and 33% respectively, with non-combustible renewables providing 39% conversion [41]. Hydroelectric is the most efficient, boasting 90% conversion efficiency [42].

Flared Methane and Stranded Energy. As mentioned earlier, methane has a far higher warming impact than CO_2 if left unchecked. Whilst flaring, or burning, of vented methane from oil and gas operations can reduce the impact substantially, the flaring process is negatively impacted by strong wind. Venting of methane is a necessary part of the drilling process, and although all vented methane is useful as fuel, distributing it can be cost prohibitive, and thus, it is simply burned to reduce environmental impact. Since 2017, when Upstream Data pioneered the concept, Bitcoin miners have been going directly to the oil and gas fields with a containerised mining and generator solution, plumbing directly into the site's flared gas line, and allowing oil and gas providers to ensure a maximum reduction in environmental impact from methane, as well as earn a profit from this source of waste [45]. Empirical research from the field has shown a reduction of 63% of emissions is achieved from using methane as an energy source for mining when compared to flaring alone [64]. In 2021, Upstream was joined by other well-funded private companies Giga Energy, Crusoe Energy, Great American Mining, Nakamotor Partners, and Jai Energy [40]. making enough of an impact on the West Texas Energy Grid to draw the attention and praise of Texas Senator Ted Cruz at the 2021 Texas Blockchain Summit [40]. In 2022, two of the largest Oil and Gas companies in the world, Exxon-Mobil and ConocoPhillips confirmed that they had also entered the flared Bitcoin mining game [66]. This comes to no surprise for industry experts, as mining using flared gas has been described by veteran industry investor and analyst that "Flared gas mitigation is as close to a free lunch as you can get," [40] and it would be rational to expected that every single oil and gas producer will attempt to eat this free lunch as the years progress.

Flared methane is only one example of a remote, isolated, or stranded source of energy. Due to the modularity possible with Bitcoin mining, there is almost nowhere on Earth that Bitcoin miners cannot or will not move their operation to for the right incentive.

Curtailed Energy and Load Balancing. Energy curtailment is when produced, but unsold, energy is allowed to go to waste by the producer, typically when cost of sale exceeds cost of production. In China in 2016 and 2017 alone, 100 TWh of solar, hydroelectric and wind power, enough to power the entire Bitcoin network for almost a year, was curtailed [46]. In 2018, this figure improved due to Bitcoin miners ramping up operations in Yunnan province to capture the cheap energy [47]. In the USA, specifically, the Texas ERCOT grid, 100 MW of Bitcoin mining power is being used as a Controllable Load Resource (CLR) [48]. Due to the ability of Bitcoin miners to effectively switch their operations on or off at a whim, software solutions providers such as Lancium are allowing miners in Texas to dial directly into the utility provider's data feeds, and level energy demand automatically [49]. Indeed, this system was put in play in March 2022 when Bitcoin miners shut down their operations to help the ERCOT grid brace for a freak winter storm [66].

Non-rival. The characteristic that waste, stranded and curtailed energy sources mentioned above share, is that they would all remain wasted, stranded and curtailed if there were no electrical loads as dynamic and flexible as Bitcoin. These are non-rival energy sources, meaning that Bitcoin miners are not competing with other customers to obtain this power.

4 Bitcoin's Current Energy Use and Emissions

Electricity Use. The Cambridge Bitcoin Electricity Consumption Index (CBECI) estimated that the Bitcoin network demanded 17.30 gigawatts (GW) of power as of 30 April 2022, which is equivalent to 151.65 TWh per year [50]. Based on a network hashrate of 213.4 EH/s on that day, this equates to an assumed average network efficiency of 0.081 W/GH, substantially less efficient than the current state of the art S19 Pro (0.0295 W/GH) mentioned earlier, but more efficient than the Antminer S9 (0.098 W/GH). Whilst the S9 was still powering 30% of the network in October 2021 due to huge energy arbitrage opportunities based on Bitcoin's all-time-high price at the time, the current proportion is substantially less [40]. Therefore, a more appropriate, and still highly conservative average network efficiency of 0.07 W/GH is assumed for all energy and efficiency related figures in this paper, resulting in an electricity demand of 130.9 TWh per year. This can be backed up by looking at Fig. 2, where over the past 4 years, there has rarely been an ASIC produced that is less efficient than 0.05 W/GH. Cambridge concedes that knowing the exact composition of mining equipment on the network is difficult, if not impossible, without voluntary industry participant disclosure. Principles of competitive economics leads to the conclusion that miners will necessarily have to upgrade their equipment to remain competitive, and therefore, power demand may be as low as 6.61 GW, or, 58 TWh per year, if it is optimistically assumed that most operating mining rigs are state of the art [50].

Energy Use. Based on the sustainable electricity mix shown in Fig. 6, heavily dominated by Natural Gas (30%) and Hydroelectric Use (30%) [21], the Bitcoin network has an estimated conversion efficiency of 53%. Therefore, the 130.9 TWh of electrical energy used by Bitcoin requires 247.0 TWh of primary energy to produce. Using the 247.0 and 130.9 TWh figures respectively calculated earlier as a baseline means that Bitcoin consumes 0.14% of the world's 173,000 TWh of energy production, or 0.5% of the world's 26,000 TWh of electricity production. In terms of "energy rankings" among countries, based on 2019 figures from OWID representing only 79 countries, Bitcoin would be the 63^{rd} ranked country in the world, between Ecuador (206.5 TWh) and New Zealand (254.5 TWh) [36]. In terms of electricity, 2020 OWID data from 70 countries places Bitcoin at rank 28, in between Ukraine (133.5 TWh) and The Netherlands (122.7 TWh) [35]. Emissions-wise, Bitcoin would rank 80^{th} out of 2019 countries, in between The Domincan Republic (38.2 MT CO_2e) and Denmark (36.0 MT CO_2e) [38] (Fig. 5).

Country	Rank	Energy Used (TWh) (2020)
Portugal	59	289.7
Hungary	60	275.9
Morocco	61	263.6
New Zealand	62	254.6
Bitcoin		**246.9**
Ecuador	63	207.5
Bulgaria	64	206.7
Trinidad and Tobago	65	198.3
Denmark	66	193.6

Country	Rank	Electricity Used (TWh) (2019)
Poland	23	157.6
Norway	24	142.9
Pakistan	25	132.7
Argentina	26	132.0
Bitcoin		**130.9**
Netherlands	27	122.7
Kazakhstan	28	103.6
Philippines	29	98.3
Belgium	30	87.5

Country	Rank	Emissions (MT CO_2e) (2020)
Syria	76	42.0
North Korea	77	40.3
Tunisia	78	38.7
Dominican Republic	79	38.2
Bitcoin		**36.6**
Denmark	80	36.0
Lebanon	81	35.7
Jordan	82	35.0
Angola	83	30.5

Fig. 5. Bitcoin energy and electricity use compared to other nations [35,36].

Emissions and Intensity. Whilst miners, especially privately held ones, may be reluctant to disclose specific details about their commercial agreements or composition of their mining rig fleet for commercial reasons, many miners have elected to voluntarily self-report their energy mixes. Formed in 2021, the Bitcoin Mining Council represents 33% of the network hashrate, and provides quarterly updates on sustainable power mix [56].

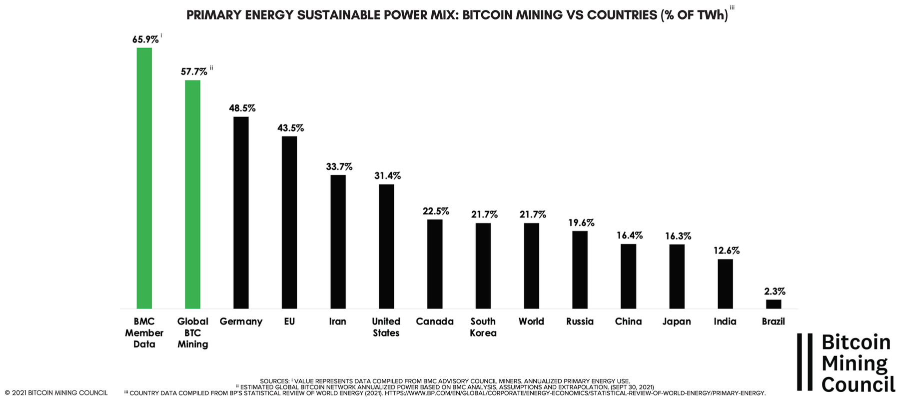

Fig. 6. Bitcoin Sustainable Energy Mix 2021. Sustainable sources include Renewables, Hydroelectric and Nuclear Energy [57].

Based on data collected post-China migration in 2021, and shown in Fig. 6, the membership of the Bitcoin Mining Council drew its power from 65.9% sustainable, low-emissions sources, with an estimate that 57.7% of the entire network is powered by low-carbon, sustainable sources (i.e. renewables + nuclear and hydroelectric). In contrast, the world average energy mix is only 21.7% sustainable, The USA at 31.4%, and The EU at 43.5%. In research by The Cambridge University Centre for Alternative Finance (CCAF) in late 2020, prior to the China ban, it was estimated that up to 49% of Bitcoin was powered by sustainable sources (10% Nuclear, 28% Hydroelectric, 11% Wind, Solar and other renewables) [58]. That same report found that 65% of Chinese miners used coal as their energy source. Therefore, a jump from 49% sustainable to 57.7% post-migration is to be expected.

In terms of emissions, the 49%-sustainable CCAF scenario resulted in 418.5 g CO_2eq/kWh, skewed quite dramatically by coal use in China. Post-migration, in the 57.7%-sustainable BMC scenario, the carbon intensity dropped by almost a third to 280 g CO_2eq/kWh [21]. Whilst quite dramatic, the China migration meant that 65% of 50% of the network was no longer powered by high-percentile emitting coal, but to far cleaner natural gas and renewable sources. As shown in Fig. 4, worst-in-class coal plants emit 6 times more than best-in-class non-CCS Natural Gas plants, and almost 26 times more than best-in-class CCS Natural Gas plants. Even 75^{th}-percentile Natural Gas plants emit far less than best-in-class coal plants. The Chinese migration has reduced the use of coal on the network dramatically, having an overall effect of increasing the sustainable energy mix of the network by almost 15%.

Using our figure of 130.9 TWh per year for electricity consumption, and an assumed carbon intensity of 280 g CO_2eq/kWh, or 0.28 MTeq/TWh, we arrive at 36.6 MT CO_2eq emitted. This is roughly 0.07% of the world's 49360 MT of GHG emissions cited earlier.

5 The Next Decade in Bitcoin Mining

Whilst it is impossible to tell the future, knowing that the nature of competition in Bitcoin mining is near-perfect, and becoming increasingly perfect with time, logical conclusions can be made. Many topics have been discussed in this paper except for the speculative subject of Bitcoin's price. Effectively, Bitcoin miners mine bitcoin when the cost to mine is cheaper than market price, or when mining is the only means available to acquire bitcoin. When the gap between cost and price is large, fierce competition and innovation closes the gap. When cost and price are similar, as in extended bear markets, only the most efficient miners survive to see better days. One thing is for certain, as Bitcoin's price climbs, more energy will be spent in the pursuit of its acquisition. For example, if a speculative bubble sent the bitcoin price to, say, $1 million, with a cost to mine of, say, only $50,000 (i.e. $950,000 profit per mined bitcoin), competition for securing scarce hardware to mine may drive hardware prices so high, that traditional firms like Intel may opt to profit by providing hardware to Bitcoin miners to capture the high premium. Indeed, as of April 2022, Intel is now a player in the ASIC manufacturing game, partnering up with soon to be public miner GRIID, who will purchase 25% of Intel's manufacturing output [67]. Whilst ASIC manufacture may not be as "free" a lunch as flared methane mining, should Intel see commercial success with their foray into the industry, their competitors are sure to follow.

Mining Industry Outlook. In line with the principles discussed in Sect. 2, we should expect strong competition, and importantly, horizontal and vertical integration to the point where there are three to four players dominating 80% of the Bitcoin mining space [20,22,23]. A fully integrated Bitcoin mining company would provide their own power and hosting sites, as well as design, fabricate, mine with, and sell their own mining hardware. With 20-year-long agreements currently being formed between large US-based miners and utilities [62], tighter integration is the natural next step. Finally, in addition to the handful of public miners today, many more miners will likely go public in order to scale and gain access to capital markets.

Carbon Intensity and Emissions. The International Energy Agency (IEA) have a Sustainable Design Scenario (SDS) which sets out energy and emissions goals from 2020 to 2050 [60]. The United Nations also has 17 Sustainable Development Goals (SDGs) calling for dramatic decarbonisation of world grids. As Bitcoin generally relies upon "the grid", general decarbonisation efforts will positively improve Bitcoin's carbon intensity profile. However, due to the economic incentives on offer for mining with wasted and stranded energy and acting as a controllable load resource, Bitcoin should improve at a far faster pace than the world grid. Due to continual improvement in mining equipment efficiency and the Chinese migration, 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 50^{th}-percentile) Natural Gas, an emissions drop in emissions of between 70 to 80% per unit of energy, despite energy use trending upwards [39]. 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.

Energy Use. So long as mining a coin is cheaper than buying one, energy will be dedicated to mining bitcoin. Theoretically, there is no bound to how much energy the Bitcoin network could use. Practically however, there is a physical limit to how many hashes can be performed per second, i.e., there are only so many application-specific Bitcoin mining chips that can be manufactured. Depending on the price of bitcoin and the amount of profit on offer, a future where power plants are built by investors for the single purpose of mining bitcoin could be imagined.

Technological Innovation and Constraints. Although physical production can be hampered by chip shortages and supply chain difficulties, it is difficult to hamper the human mind and entrepreneurial spirit. Thus, even though chips aren't being shipped as frequently, or in as large a quantity, improvement and innovation is not slowing down. The Antminer S9, released in 2018 had 16 nm (nm) architecture, the S17 and S19 in 2017 and 2019, respectively, had 7 nm architecture, and the upcoming S19XP will be 5 nm [29]. The world's largest semiconductor company, TSMC, will be releasing 3 nm and 2 nm processes in 2023 and 2025 respectively [63]. It can be expected that the efficiency gains of

25–30% between architecture generations will continue for the majority of the next decade, especially with commodification of mining equipment to happen near decade's end (Fig. 7).

	Energy Produced (TWh)	**Electricity Generated (TWh)**	**Total Emissions (MT CO2e)**	**Grid Intensity (g CO_2e/kWh)**
World	173000	26000	49360	487
USA	*26291*	*4049*	*5833*	*405*
EU	*16896*	*2760*	*3162*	*269*
China	*39361*	*7623*	*11577*	*613*

	Energy Consumed (TWh)	**Electricity Consumed (TWh)**	**Total Emissions (MT CO2e)**	**Grid Intensity (g CO_2e/kWh)**
Bitcoin	247.0	130.9	36.7	280
% of World	0.14%	0.50%	0.07%	57.49%

Fig. 7. Summary of Key Data. *Bitcoin data as at 9 December 2021* [50, 56]. *Emissions data as at 2016* [52]. *Energy data as at 2019* [35]. *Grid intensity data as at 2020* [55].

6 Conclusion

This paper has discussed the drivers of energy use, and thus, emissions, of Bitcoin mining. Whilst the fundamental driver is profit, the drive to survive amidst near-perfect competition makes Bitcoin mining a unique landscape. Whilst Bitcoin does use a large amount of energy, it was shown that the use is negligible on a global scale, and far cleaner than the world or US average on a per unit of energy basis. Most importantly, Bitcoin's current role as a buyer-of-last-resort for stranded or wasted assets, and being a driver of innovation in energy markets as a buyer-of-first-resort, will play a pivotal part in greening the world's grids and achieving the IEA and UN's sustainability goals.

References

1. Nakamoto, S.: Bitcoin: A Peer-to-Peer Electronic Cash System (2008). https://www.bitcoin.org/bitcoin.pdf. Accessed 8 Dec 2021
2. Bitcoin Wiki: Difficulty (2021). https://en.bitcoin.it/wiki/Difficulty. Accessed 8 Dec 2021
3. River Financial: Block Subsidy. https://river.com/learn/terms/b/block-subsidy/. Accessed 8 Dec 2021

4. River Financial: What Is a Bitcoin Halving?. https://river.com/learn/what-is-a-bitcoin-halving/. Accessed 8 Dec 2021
5. Lutz, G.: Application specific integrated circuits. In: XXIV International Conference on High Energy Physics, pp. 1249–1255 (1989). https://doi.org/10.1007/978-3-642-74136-4_147
6. Bitcoin Wiki: Hashrate. https://en.bitcoinwiki.org/wiki/Hashrate. Accessed 8 Dec 2021
7. Parkin, M.: Microeconomics, 11th edn., pp. 272–296. Pearson, New York (2014)
8. Mankiw, N.: Principles of Economics, 6th edn., pp. 291–314. South-Western Cengage, Mason (2001)
9. Makowski, L., Ostroy, J.: Perfect competition and the creativity of the market. J. Econ. Lit. **XXXIX**, 479–535 (2001)
10. Stiglitz, J., Walsh, C.: Economics, 4th edn., pp. 205–222. W.W. Norton & Company, New York (2006)
11. Dean, J.: Managerial Economics. Prentice Hall, New York (1951)
12. Semulson, W., Marks, J.: Managerial Economics, 7th edn., pp. 283–318. Wiley, New York (2012)
13. Bitcoin Wiki: Seed Phrase. https://en.bitcoin.it/wiki/Seed_phrase. Accessed 8 Dec 2021
14. Lightning Network: Lightning Network Homepage (2021). https://lightning.network/. Accessed 8 Dec 2021
15. Crypto.com: 2021 Crypto Market Sizing Report & 2022 Forecast (2022). https://crypto.com/research/2021-crypto-market-sizing-report-2022-forecast/
16. Wile, R.: Today, Bitcoin's Doomsday Scenario Arrived. BusinessInsider.com.au (2014). https://www.businessinsider.com.au/today-bitcoins-doomsday-scenario-arrived-2014-6?r=US&IR=T. Accessed 8 Dec 2021
17. Cambridge Centre for Alternative Finance: Bitcoin Mining Map. University of Cambridge (2021). https://ccaf.io/cbeci/mining_map. Accessed 20 Mar 2022
18. Attinasi, M., et al.: The semiconductor shortage and its implication for euro area trade, production and prices, Econ. Bull. Boxes **4** (2021)
19. Glassnode Studios: Bitcoin Hash Rate. Glassnode Studios (2022). https://studio.glassnode.com/metrics?a=BTC&category=Miners&m=mining.HashRateMean. Accessed 30 Apr 2022
20. Henderson, B.: The Rule of Three and Four. Boston Consulting Group (1976)
21. McCook, H.: Bitcoin's energy use compared to other industries. Bitcoin Magazine (2021). https://bitcoinmagazine.com/business/bitcoin-energy-use-compare-industry. Accessed 8 Dec 2021
22. Sheth, J., Sisodia, R.: Competitive Markets and the Rule of Three. Ivey School of Business, London (2002)
23. Pareto, V.: Manual of Political Economy. Oxford University Press, Oxford (2014)
24. MiningPoolStats: Bitcoin Hashrate Distribution (2021). https://miningpoolstats.stream/bitcoin. Accessed 20 Mar 2022
25. Afuah, A.: Innovation Management: Strategies, Implementation and Profits, 1st edn., pp. 13–46. Oxford University Press, Oxford (1998)
26. Cambridge Centre for Alternative Finance: CBECI SHA-256 Mining Equipment List (2021). https://sha256.cbeci.org. Accessed 8 Dec 2021
27. Cambridge Centre for Alternative Finance: CBECI Methodology (2021). https://ccaf.io/cbeci/index/methodology. Accessed 8 Dec 2021
28. International Energy Agency: Key World Energy Statistics (2021). https://iea.blob.core.windows.net/assets/52f66a88-0b63-4ad2-94a5-29d36e864b82/KeyWorldEnergyStatistics2021.pdf. Accessed 8 Dec 2021

29. Compass Mining: The Antminer S19XP: What is it? (2021). https://compassmining.io/education/bitmain-antminer-s19xp/. Accessed 8 Dec 2021
30. International Panel on Climate Change: Special Report on Renewable Energy Sources and Climate Change Mitigation (2012). https://archive.ipcc.ch/pdf/special-reports/srren/SRREN_FD_SPM_final.pdf. Accessed 8 Dec 2021
31. United States Environmental Protection Agency: Global Greenhouse Gas Emissions Data (2019). https://www.epa.gov/ghgemissions/global-greenhouse-gas-emissions-data. Accessed 8 Dec 2021
32. The World Bank: Global Gas Flaring Tracker Report - July 2020, p. 5 (2020). https://pubdocs.worldbank.org/en/503141595343850009/WB-GGFR-Report-July2020.pdf. Accessed 8 Dec 2021
33. United Nations Framework Convention on Climate Change: Global Warming Potentials (IPCC Second Assessment Report). https://unfccc.int/process/transparency-and-reporting/greenhouse-gas-data/greenhouse-gas-data-unfccc/global-warming-potentials. Accessed 8 Dec 2021
34. MIT Digital Currency Initiative: 51% attacks (2020). https://dci.mit.edu/51-attacks. Accessed 8 Dec 2021
35. OurWorldInData.org: Global primary energy consumption by source. University of Oxford (2021). https://ourworldindata.org/energy-production-consumption. Accessed 8 Dec 2021
36. OurWorldInData.org: Electricity Mix. University of Oxford (2021). https://ourworldindata.org/electricity-mix. Accessed 8 Dec 2021
37. OurWorldInData.org: Access to Energy. University of Oxford (2019). https://ourworldindata.org/energy-access. Accessed 8 Dec 2021
38. OurWorldInData.org: Data on CO2 and Greenhouse Gas Emissions by Our World in Data. https://github.com/owid/co2-data. Accessed 30 Apr 2022
39. McCook, H.: Projecting Bitcoin's Future Energy Use. Bitcoin Magazine (2021). https://bitcoinmagazine.com/business/projecting-bitcoins-future-energy-use. Accessed 8 Dec 2021
40. Carter, N.: Bitcoin Mining Is Reshaping the Energy Sector and No One Is Talking About It. Coindesk.com (2021). https://www.coindesk.com/policy/2021/10/11/bitcoin-mining-is-reshaping-the-energy-sector-and-no-one-is-talking-about-it/. Accessed 8 Dec 2021
41. U.S Energy Information Administration: Table A6 Approximate Heat Rates for Electricity, and Heat Content of Electricity. U.S. Energy Information Administration (2021). https://www.eia.gov/totalenergy/data/browser/index.php?tbl=TA6#/?f=A. Accessed 8 Dec 2021
42. Killingtveit, A.: 15 - Hydroelectric Power. Future Energy, 3rd edn., pp. 315–330. Elsevier (2020). https://doi.org/10.1016/B978-0-08-102886-5.00015-3
43. Riot Blockchain Inc: Riot announces first industrial-scale immersion-cooled Bitcoin mining operation (2021). https://www.riotblockchain.com/investors/news-events/press-releases/detail/117/riot-announces-first-industrial-scale-immersion-cooled. Accessed 8 Dec 2021
44. Mawson Infrastructure Group Inc.: Infrastructure and Hosting (2021). https://mawsoninc.com/infrastructure-hosting/. Accessed 8 Dec 2021
45. Upstream Data: Homepage (2021). https://www.upstreamdata.ca/. Accessed 8 Dec 2021
46. Dong, W., Qi, Y.: Utility of renewable energy in China's low-carbon transition. Brookings (2018). https://www.brookings.edu/2018/05/18/utility-of-renewable-energy-in-chinas-low-carbon-transition/. Accessed 8 Dec 2021

47. Carter, N.: Noahbjectivity on Bitcoin Mining (2021). https://medium.com/@nic_carter/noahbjectivity-on-bitcoin-mining-2052226310cb. Accessed 8 Dec 2021
48. Potomac Economics: 2020 State of the Market Report for the ERCOT electricity markets (2021). https://www.potomaceconomics.com/wp-content/uploads/2021/06/2020-ERCOT-State-of-the-Market-Report.pdf. Accessed 8 Dec 2021
49. Lancium: Homepage (2021). https://lancium.com/. Accessed 8 Dec 2021
50. Cambridge Centre for Alternative Finance: Cambridge Bitcoin Energy Consumption Index. University of Cambridge, Judge Business School (2021). https://ccaf.io/cbeci/index. Accessed 8 Dec 2021
51. OurWorldInData.org: CO_2 emissions. University of Oxford (2019). https://ourworldindata.org/co2-emissions. Accessed 8 Dec 2021
52. OurWorldInData.org: Greenhouse Gas Emissions. University of Oxford (2019). https://ourworldindata.org/greenhouse-gas-emissions. Accessed 8 Dec 2021
53. OurWorldInData.org: Energy Production and Consumption. University of Oxford (2019). https://ourworldindata.org/energy-production-consumption. Accessed 8 Dec 2021
54. OurWorldInData.org: Electricity Production by Source, World. University of Oxford (2019). https://ourworldindata.org/grapher/electricity-prod-source-stacked. Accessed 8 Dec 2021
55. International Energy Agency: Carbon intensity of electricity generation in selected regions in the Sustainable Development Scenario, 2000–2040 (2020). https://www.iea.org/data-and-statistics/charts/carbon-intensity-of-electricity-generation-in-selected-regions-in-the-sustainable-development-scenario-2000-2040. Accessed 8 Dec 2021
56. Bitcoin Mining Council: Homepage (2021). https://bitcoinminingcouncil.com/. Accessed 8 Dec 2021
57. Bitcoin Mining Council: Global Bitcoin Mining Data Review - Q3 2021 (2021). https://bitcoinminingcouncil.com/wp-content/uploads/2021/10/2021.10.19-Q3-BMC-Presentation-Materials-Final.pdf. Accessed 8 Dec 2021
58. Cambridge Centre for Alternative Finance: 3rd Global Cryptoasset Benchmarking Study. University of Cambridge (2020). https://www.jbs.cam.ac.uk/wp-content/uploads/2021/01/2021-ccaf-3rd-global-cryptoasset-benchmarking-study.pdf. Accessed 8 Dec 2021
59. Lazard: Levelized Cost of Energy, Levelized Cost of Storage, and Levelized Cost of Hydrogen 2020 (2020). https://www.lazard.com/perspective/lcoe2020. Accessed 8 Dec 2021
60. International Energy Agency: The Sustainable Development Scenario (2019). https://iea.blob.core.windows.net/assets/ebf178cc-b1c9-4de9-a3aa-51a080c0f8c3/SDS-webinar-2019-draft06.pdf. Accessed 8 Dec 2021
61. United Nations Department of Economic and Social Affairs - Sustainable Development: The 17 Goals (2021). https://sdgs.un.org/goals. Accessed 8 Dec 2021
62. DiCamillo, N.: Bitcoin Mining Firm Compass Inks Deal With Nuclear Microreactor Company Oklo. Coindesk (2021). https://www.coindesk.com/business/2021/07/14/bitcoin-mining-firm-compass-inks-deal-with-nuclear-microreactor-company-oklo/. Accessed 8 Dec 2021
63. Shilov, A.: TSMC Roadmap Update: 3 nm in Q1 2023, 3 nm Enhanced in 2024, 2 nm in 2025. Anandtech (2021). https://www.anandtech.com/show/17013/tsmc-update-3nm-in-q1-2023-3nm-enhanced-in-2024-2nm-in-2025. Accessed 20 Mar 2022

64. Crusoe Energy: Understanding The Problem Crusoe Solves (2021). https://www.crusoeenergy.com/blog/3MyNTKiT6wqsEWKhP0BeY/understanding-the-problem-crusoe-solves. Accessed 20 Mar 2022
65. Sigalos, M.: These 23-year-old Texans made $4 million last year mining bitcoin off flare gas from oil drilling (2022). https://www.cnbc.com/2022/02/12/23-year-old-texans-made-4-million-mining-bitcoin-off-flared-natural-gas.html. Accessed 20 Mar 2022
66. Sigalos, M.: Bitcoin miners are helping the Texas grid brace for winter storm impact (2022). https://www.cnbc.com/2022/02/03/winter-storm-descends-on-texas-bitcoin-miners-shut-off-to-protect-ercot.html. Accessed 20 Mar 2022. CNBC, https://www.cnbc.com/2022/03/26/exxon-mining-bitcoin-with-crusoe-energy-in-north-dakota-bakken-region.html
67. Alcorn, P.: Intel's Second-Gen Bitcoin Miner's Performance and Pricing Listed, Leads the Market (2022). https://www.tomshardware.com/news/intels-second-gen-bitcoin-miners-performance-and-pricing-listed. Accessed 20 Mar 2022