The Energy Footprint of Bitcoin Mining: A Critical Perspective

Antonio Levato

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Abstract

Bitcoin is one of the most relevant and successful investment of recent years, but its environmental consequences are significant. This paper explores the dynamics behind the Bitcoin mining industry and its relevant effects. It analyzes the conditions under which mining remains profitable, compares the energy efficiency of various mining farms and reviews the technologies employed in the process. The goal is to evaluate the sustainability of Bitcoin's energy consumption and suggest possible improvements or alternatives.

1 Introduction

Bitcoin is a decentralized digital currency introduced in 2008 by an anonymous individual under the pseudonym Satoshi Nakamoto. It was officially launched in 2009 with the aim of enabling peer-to-peer transactions over a decentralized network called blockchain. Unlike traditional fiat currencies such as the Euro or the US Dollar, Bitcoin is not controlled by any central authority. Its underlying technology, blockchain, is based on principles of integrity, transparency, and authenticity.

These characteristics have contributed to Bitcoin's success and popularity, quickly establishing it as one of the most revolutionary instruments in the world of digital payments. However, alongside its technological innovation and financial potential, Bitcoin has raised serious environmental concerns, primarily due to the process known as mining.

As this paper is intended for an informed audience, basic concepts such as blockchain operation and mining will only be briefly mentioned, in order to focus directly on the main topics.

2 Origins

Miners (nowadays, mostly mining farms) compete in a process aimed at finding a nonce: a random number that solves the hash equation. This computation is complex and its resolution time and procedures have evolved significantly since 2009. Unfortunately, this step is not skippable, as it enables the addition of new verified blocks to the blockchain.

This type of problem is difficult to solve and its complexity increases over time. In the early days, anyone could mine using a CPU or a regular laptop from home and still earn a profit. Today, however, mining has changed dramatically. Investors have built large mining hubs equipped with more powerful units and advanced cooling systems to handle the growing computational demands of solving cryptographic puzzles.

For this reason, miners now use ASICs and other powerful hardware to perform these kinds of calculations. It is intuitive to understand that such energy requirements lead to higher electricity demand and, consequently, increased costs. Of course, most people are willing to pay high energy bills if that is the price for obtaining mining rewards, but, since only one miner ultimately gets the reward, it is a high-stakes competition and, in such a scenario, no one would be happy to lose.

Mining could be profitable for someone, but, for sure, it causes several diseases to our planet and lives.

3 Technologies

Technologies used for Bitcoin mining have changed significantly over time, primarily driven by the increasing difficulty of mining and the desire for greater efficiency. Here is a panoramic view of devices used in the process.

Table 1: Bitcoin Mining Hardware – Evolution and Energy Profile

Hardware Type	Period of Use	Hash Rate	Energy Efficiency (J/TH)	Energy Demand (total)	Notes
CPU	2009 – ∼2010	0.01 GH/s	Very low (inefficient)	High per hash, low total	Obsolete; used only in early days
GPU	∼2010 – ∼2012	Up to 1 GH/s	Low	Moderate to high	Better than CPU, still not optimized
FPGA	∼2011 – ∼2013	25 – 100+ MH/s	Medium (50–100 J/TH)	Moderate	Short-lived; niche use
ASIC (early gen)	2013 – ∼2016	0.5 – 4 TH/s	Good (30–50 J/TH)	High	First efficient dedicated hardware
ASIC (modern)	2017 – present	90 – 250+ TH/s	Excellent (21–29 J/TH)	Very high	Dominant today; industrial-scale use

As the mining industry evolved, the technologies involved became increasingly less affordable and more specialized. Entering the mining market today requires a significant investment in dedicated hardware, as basic or outdated equipment is no longer sufficient to compete effectively. This shift reflects how Bitcoin mining has reached a threshold beyond which only high-performance infrastructure can ensure profitability.

The introduction of ASICs marked a major turning point, dramatically improving both hash rate and energy efficiency. However, while modern ASICs are considerably more efficient in terms of energy consumption per terahash (as low as 21 J/TH), their widespread deployment in industrial-scale mining operations results in extremely high overall electricity demand.

This reveals a critical paradox: despite ongoing technical improvements in hardware efficiency, the total environmental footprint of Bitcoin mining continues to expand due to the sheer volume of operations. Efficiency at the unit level does not necessarily translate into sustainability at the system level.

4 Environmental footprint

One of the most concerning aspects of Bitcoin mining is its increasing energy demand. The following table illustrates the rapid growth in electricity consumption over the period from 2010 to 2023.

Table 2: Bitcoin Mining Energy Consumption (2010–2023)

Year	Yearly Consumption (TWh)	Cumulative Consumption (TWh)
2010	0.00	0.00
2011	0.14	0.14
2012	0.10	0.24
2013	1.06	1.30
2014	4.73	6.03
2015	3.62	9.65
2016	5.73	17.38
2017	12.93	28.30
2018	43.32	71.63
2019	54.63	126.26
2020	67.14	193.40
2021	89.00	282.40
2022	95.53	377.93
2023	121.13	499.06

Consider the following plot and focus on how the electricity consumption curve has evolved.

Since the beginning of the observed period, the growth in energy demand has followed an exponential trend, driven by the increasing computational power required to mine Bitcoin efficiently. This surge can be attributed to the intensifying competition among miners, which pushes for the continuous upgrade of hardware to remain profitable.

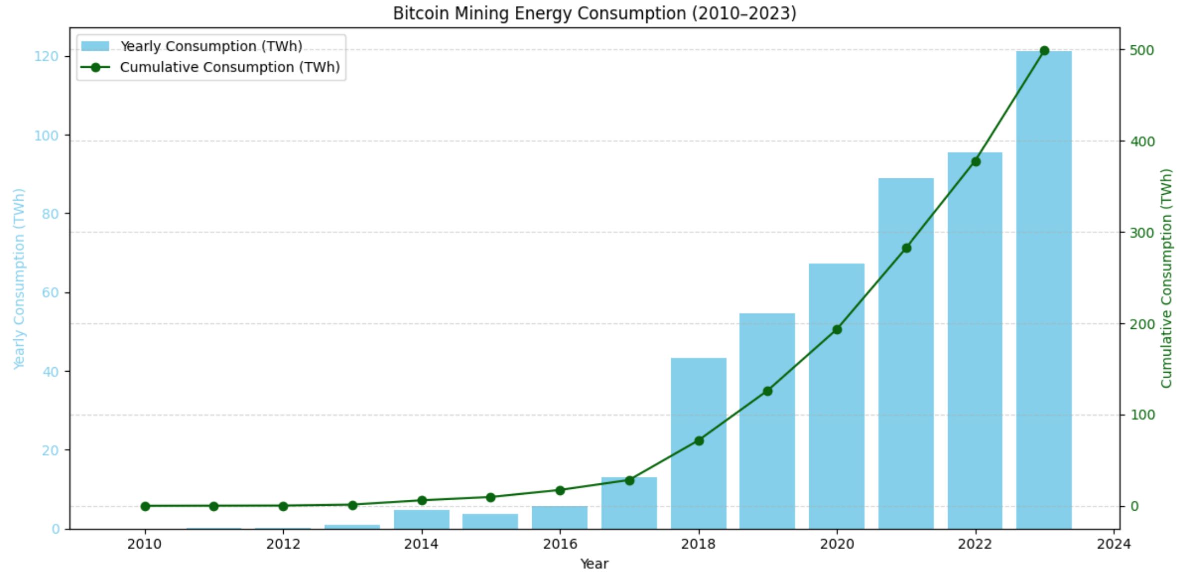

Figure 1: Bitcoin mining yearly and cumulative energy consumption from 2010 to 2023. The bars represent yearly consumption (in TWh), while the green curve shows the cumulative energy used over time.

Energy demand remained marginal until 2016, but from 2017 onward there was a significant surge. Yearly consumption rose from 12.9 TWh in 2017 to over 121 TWh by 2023, reflecting the industrialization of mining practices and the global spread of large-scale mining farms.

As a result, the cumulative energy consumption curve shows accelerated exponential growth, surpassing 499 TWh by 2023. This trajectory highlights Bitcoin mining's growing environmental footprint and underscores the urgent need for strategies that can balance network security with sustainable energy use.

In fact, Bitcoin mining has become one of the most energy-consuming computational processes in the world. In September 2021, it was estimated that Bitcoin alone consumed about 0.5% of global electricity, more than seven times the energy used annually by Google. The electricity demand varies greatly depending on mining hardware, location, and electricity cost. Regions with cheap energy, such as China, regions of the U.S., Kazakhstan and Northern Europe have become attractive hubs for mining operations.

At this point, a cycle starts: more electricity demand, more fossil fuels used to provide electricity, more carbon dioxide emissions, more climate changes. Overcoming these aspects, there is an ethical aspect to consider: power shortages and blackouts. This mean that most of the population of the surrounding areas of mining hubs could have several problems because of energetic inefficiencies: on one side, miners have consistent profits; on the other side, people pay consequences of this business.

These environmental and ethical challenges highlight the urgent need to rethink the energy model behind Bitcoin mining and explore more sustainable alternatives.

4.1 Theoretical Lower Bound and Theoretical Upper Bound

Before going deeper in detail, it is necessary to introduce two estimates of energy consumption: theoretical lower bound and theoretical upper bound. Those values, explained by Küfeoğlu and Özkuran in their publication, but globally recognized by the whole community, are analytical tools useful to evaluate the full spectrum of possible energy outcomes in the Bitcoin mining ecosystem. By defining what is technically and economically plausible, they allow for more accurate comparisons across different estimation models and provide a reference point for assessing the environmental impact of mining operations.

In particular, we define theoretical lower and upper bounds respectively as:

- The estimated energy consumption of the Bitcoin network under the assumption that all miners use the most energy-efficient hardware available on the market at each difficulty adjustment. This represents an idealized best-case scenario in terms of technological efficiency.

- The maximum level of energy consumption at which Bitcoin mining remains economically viable, assuming the use of the least efficient hardware that can still generate profits given current electricity prices and Bitcoin market value. This represents a worst-case scenario in terms of environmental impact.

These boundaries are not meant to provide a precise prediction, but rather to define an analytical envelope within which the actual energy consumption is expected to fall. The theoretical lower bound is quantified by multiplying the network hashrate by the energy efficiency of the most efficient hardware available:

$$P_{\min} = \frac{NH \cdot \mathrm{Min}(EoH)}{10^{12}} \tag{1}$$

- NH is the network hashrate.
- $Min(EoH)$ is the minimum energy per terahash.

On the other hand, the theoretical upper bound is defined as the point where Bitcoin mining becomes nonprofitable due to electricity costs exceeding revenues. It is calculated based on the worst-performing hardware that is still economically viable:

$$P_M = \frac{NH \cdot \mathrm{Max}(EoH)}{10^{18}} \tag{2}$$

- $Max(EoH)$ is the maximum energy per terahash.

It is important to note that, while both $P_{\min}$ and P_M provide useful analytical boundaries, an increase in either of these values corresponds to a higher estimated power demand. Therefore, if either the network hashrate (NH) or the hardware energy efficiency (EoH) worsens, the theoretical energy consumption also increases proportionally. This implies that growing competition among miners or slower adoption of more efficient devices may result in greater environmental impact.

However, based on the sources and discussions, energy consumption values related to cryptocurrencies, particularly Bitcoin, must be interpreted with caution. Several factors contribute to the risk of misleading or overconfident estimates:

- Static assumptions: many estimation models rely on fixed values for electricity price and Bitcoin market value, which are both highly volatile and subject to significant fluctuations.
- Geographic variation: electricity prices vary widely between and within countries. Using a constant rate, such as 0.05 USD/kWh, may not represent real operational costs in many locations.
- Optimistic hardware models: some models assume a perfectly balanced use of profitable, up-to-date mining devices. In reality, older, less efficient models remain in operation far beyond their release period.
- Sales vs. deployment gap: hardware shipment data does not immediately translate into operational hashing power, creating discrepancies in network energy estimation.
- Data inaccessibility: mining activities are difficult to trace due to their decentralized and, often, opaque nature. The lack of transparency hinders accurate energy tracking and complicates regulation.
- Bitcoin-centric focus: focusing only on Bitcoin omits the considerable energy demand from other mineable cryptocurrencies, leading to underestimations of the overall sector impact.
- Neglected auxiliary losses: large-scale mining operations often experience additional energy losses due to cooling, distribution, and infrastructure, which are frequently unaccounted for.
- Market-driven energy demand: the Bitcoin price influences mining intensity. Ignoring price volatility can lead to static models that miss real-world dynamics.

- Methodological disparity: due to differing models and assumptions, published studies offer a wide range of estimates, further complicating clear conclusions.

In conclusion, while theoretical models like $P_{\min}$ and P_M provide useful analytical frames, they must be used alongside a critical understanding of the assumptions and limitations behind energy estimations. The dynamic nature of mining markets, technological evolution, and the opacity of mining infrastructure all call for a cautious interpretation of energy consumption figures.

4.2 The Cycle

In reference to what has been discussed so far, it is clear that the electricity demand associated with Bitcoin mining is excessive. It is worth emphasizing that this analysis has been focused solely on Bitcoin, intentionally setting aside the broader world of cryptocurrencies. This means that the environmental impact described thus far is, to some extent, underestimated, despite already being significant.

Bitcoin is currently the most widespread and capitalized cryptocurrency, enjoying a level of popularity and market integration that other digital currencies have not yet reached. However, many of these lesser-known cryptocurrencies may eventually follow the same path, especially if adoption increases. This raises a critical issue: environmental sustainability must become a central concern, not only for Bitcoin but for the entire crypto-mining industry.

Today, electricity production still largely relies on fossil fuels, with only a partial contribution from renewable sources, despite remarkable progress in recent years. One cannot help but wonder how different the situation might be had more substantial investments in green energy been made earlier. Although such a thought might sound simplistic, it reflects a painful truth.

Carbon dioxide emissions from Bitcoin mining are already substantial and when considered alongside other contributors to climate change, such as transportation, industrial processes and plastic pollution, the broader environmental outlook becomes increasingly troubling.

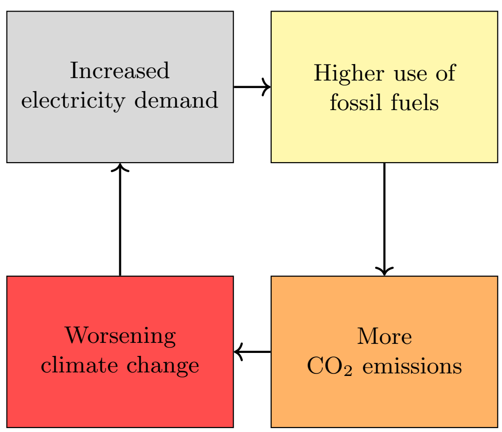

Figure 2: The feedback cycle of Bitcoin mining and environmental impact. The diagram shows how increased electricity demand feeds into higher fossil fuel consumption, which in turn drives CO_2 emissions and accelerates climate change, creating a self-reinforcing loop.

This leads us to a pressing question: can cryptocurrency mining become a sustainable and environmentally friendly business model? The answer to this question will shape not only the future of digital finance but also its compatibility with our global climate goals.

5 Practical, political and ethical solutions for sustainable mining

Fortunately, we are still in time to take meaningful action to safeguard the environment and several viable pathways are available to address this challenge. The issue is well recognized and the stakeholders involved in the crypto industry are increasingly aware of the environmental implications of their operations.

Among the most promising options is the transition from Proof-of-Work (PoW) to Proof-of-Stake (PoS) consensus mechanisms. While PoW relies on massive computational power to validate transactions, requiring miners to solve complex cryptographic puzzles, PoS shifts validation responsibility to those who hold and stake a certain amount of cryptocurrency. This drastically reduces the amount of electricity needed, making it a far more energy-efficient alternative.

In terms of energy sources, renewable energy plays a key role in reducing the carbon footprint of mining operations. Although the use of hydropower, solar, wind and geothermal energy can theoretically eliminate CO_2 emissions, it would be unrealistic to expect the mining sector to rely solely on renewables. These sources are subject to limitations such as seasonal variation and geographic feasibility: not all regions are suitable for wind farms or solar fields and installation is not always practical. Among renewables, geothermal energy currently stands out as the most promising due to its constant availability and low environmental impact.

Technological innovation is also advancing. Hardware manufacturers are actively working to develop more energy-efficient mining equipment, not only in terms of power consumption but also in reducing emissions during manufacturing. Additionally, one area of innovation includes the use of advanced cooling systems. Traditional mining farms generate large amounts of heat which leads to extra energy consumption for air conditioning. However, by adopting passive or integrated cooling systems, including heat recovery for local heating or trigeneration (heat, electricity and cooling), energy waste can be significantly reduced.

5.1 Policies and Regulations

Effective environmental action also requires solid regulatory frameworks. National and international institutions must implement policies that:

- Enhance transparency by requiring miners to disclose energy sources and consumption levels;
- Introduce economic instruments, such as higher electricity prices for non-sustainable mining, carbon taxes, or the obligation to offset emissions through environmental credits;
- Ban carbon-intensive mining operations, while offering incentives to adopt clean energy;
- Align with international climate goals, such as the Paris Agreement, which calls for urgent mitigation of emissions from all sectors, including emerging technologies like cryptocurrencies;
- Strengthen oversight by actively monitoring energy usage within the digital currency sector and treating mining activity as a regulated industry;
- Avoid implicit subsidies, such as untaxed mining revenue, which currently encourage unsustainable practices.

5.2 Ethical Behavior and Social Responsibility

Beyond technical and political action, individual and collective ethical responsibility plays a crucial role. Investors and users should favor cryptocurrencies that adopt energy-efficient protocols, such as PoS, and support mining operations powered by renewable energy.

Miners themselves must commit to greater transparency, publishing data about their environmental impact and energy use. The crypto community as a whole should promote awareness of sustainability issues and consider these in decision-making, whether investing in a token or designing a new protocol.

Furthermore, continued support for research and innovation is essential to develop next-generation technologies that are both secure and low-impact. Finally, public pressure on governments and institutions is key to pushing forward meaningful legislation that holds the crypto industry accountable and promotes greener practices.

6 Conclusion

This paper has explored the energy dynamics of Bitcoin mining, highlighting the tension between the success of a decentralized digital currency and its environmental impact. While mining has evolved into a highly competitive and technologically advanced industry, it has also become one of the most energy-intensive digital activities in the world.

The analysis revealed that although technical advancements have led to more efficient hardware, the overall energy demand has continued to rise due to the increasing scale of mining operations. Theoretical energy consumption bounds have been introduced to frame the debate and attention has been given to the feedback loop connecting mining, fossil fuel use and climate change.

Importantly, several viable pathways toward sustainability have been discussed. These options must be supported by strong regulatory frameworks and ethical behavior from individuals and institutions within the crypto ecosystem.

Bitcoin, as the most prominent cryptocurrency, has a responsibility to lead by example. Its future sustainability depends on a collective effort to align technological innovation with environmental responsibility. The choices made today will determine whether blockchain technologies can coexist with the urgent need for climate action.

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