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Article

The impact of Bitcoin mining on the carbon footprint in the Republic of Kazakhstan

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Abstract: Background: Bitcoin mining, an energy-intensive process, requires significant amounts of electricity, which results in a particularly high carbon footprint from mining operations. In the Republic of Kazakhstan, where a substantial portion of electricity is generated from coal-fired power plants, the carbon footprint of mining operations is particularly high. This article examines the scale of energy consumption by mining farms, assesses their share in the country's total electricity consumption, and analyzes the carbon footprint associated with bitcoin mining. A comparative analysis with other sectors of the economy, including transportation and industry is provided, along with possible measures to reduce the environmental impact of mining operations. Materials and methods: To assess the impact of bitcoin mining on the carbon footprint in Kazakhstan, electricity consumption from 2016 to 2023, provided by the Bureau of National Statistics of the Republic of Kazakhstan, was used. Data on electricity production from various types of power plants was also analyzed. The Life Cycle Assessment (LCA) methodology was used to analyze the environmental performance of energy systems. CO_2 emissions were estimated based on emission factors for various energy sources. Results: The total electricity consumption in Kazakhstan increased from 74,502 GWh in 2016 to 115,067.6 GWh in 2023. The industrial sector's electricity consumption remained relatively stable over this period. The consumption by mining farms amounted to 10,346 GWh in 2021. A comparative analysis of CO_2 emissions showed that bitcoin mining has a higher carbon footprint compared to electricity generation from renewable sources, as well as oil refining and car manufacturing. Conclusions: Bitcoin mining has a significant negative impact on the environment of the Republic of Kazakhstan due to high electricity consumption and resulting carbon dioxide emissions. Measures are needed to transition to sustainable energy sources and improve energy efficiency to reduce the environmental footprint of cryptocurrency mining activities.

Keywords: bitcoin mining; carbon footprint; Kazakhstan; electricity; CO_2 emissions; sustainable development

1. Introduction

Since its inception in 2008, Bitcoin, a revolutionary digital currency, has continuously sparked discussions and debates (Nakamoto, 2023; Sun et al., 2022). The cryptocurrency sector is increasingly integrating into the global financial system, driven by significant technological advancements offering several benefits (McGinn et al., 2018). However, as the demand for exchanging and investing in digital currencies rapidly grows, it is crucial to address the hidden and often overlooked environmental consequences of this growth (Narayanan et al., 2016; Chamanara et al., 2023).

The sharp rise in Bitcoin (BTC) prices over the past few years and the resulting global race for BTC mining have turned the cryptocurrency market into one of the world's most polluting sectors (de Vries, 2021; Liu et al., 2023). One major issue is the energy consumption and carbon dioxide emissions resulting from Bitcoin mining activities (Di Febo et al., 2021). The consensus algorithm used in Bitcoin mining, known as Proof of Work (PoW), involves network peers attempting to solve a hash problem, with the winner receiving a block reward and transaction fees for transactions occurring in the current block (Nakamoto, 2023). This process consumes significant amounts of electricity, analogous to extracting precious metals from the ground (He et al., 2023).

Historically, China has been the largest country involved in Bitcoin mining, contributing significantly to the global carbon footprint (Ziegler et al., 2021). To offset the carbon dioxide emissions from coal-based Bitcoin mining operations in China in 2021–2022, approximately 2 billion trees would need to be planted, covering an area equivalent to the combined territories of Portugal and Ireland or 45,000 times the area of Central Park in New York (Stoll et al., 2019). In addition to China, the top ten Bitcoin mining countries in 2020–2021 were the USA, Kazakhstan, Russia, Malaysia, Canada, Germany, Iran, Ireland, and Singapore (Ziegler et al., 2021).

COP26's ambitions to achieve global net-zero carbon emissions by 2050 are threatened by the alarming rise in the carbon footprint of the most popular blockchain networks, which resist energy-reducing technological modifications (United Nations Framework Convention on Climate Change, n.d.). Emissions caused by Proof of Work consensus protocols not only pollute the planet but also result in unnecessary human deaths (Mora, 2018).

However, our understanding of the environmental impact of BTC mining remains limited. As with the global impact of Bitcoin on electricity consumption, the growing interest in blockchain and cryptocurrencies in Kazakhstan highlights their environmental footprint (Krause and Tolaymat, 2018). Kazakhstan, with its substantial fossil fuel resources and renewable energy potential, faces a choice in developing a digital economy with environmental sustainability in mind.

Since 2020, Kazakhstan has been one of the world leaders in digital cryptocurrency mining. According to open-source data, Kazakhstan ranked second in Bitcoin mining in 2021, with an 18.1% share of the total volume, after the USA (35.4%) (Ziegler et al., 2021). This trend is due to relatively low electricity costs and the legal recognition of digital mining activities. According to the Order of the Minister of Digital Development, Innovations, and Aerospace Industry of the Republic of Kazakhstan dated 13 October 2020, No. 384/НҚ "On Approval of the Rules for Informing about Digital Mining Activities," digital mining is defined as the process of performing computational operations using computer and energy resources according to specified encryption algorithms and data processing to ensure the integrity of data blocks in information systems through blockchain (Digital Development, Innovations, and Aerospace Industry of the Republic of Kazakhstan, 2020).

Following stricter regulations in China, Kazakhstan has become one of the world's leading countries in cryptocurrency mining volumes, significantly increasing electricity consumption in this sector. Mining centers using electricity generated from coal and natural gas contribute to overall carbon dioxide emissions, raising concerns about the country's environmental sustainability (IRENA, 2020).

Globally, a significant portion of the energy used for cryptocurrency mining in Kazakhstan is from non-renewable sources, contributing to increased global carbon dioxide emissions. This harms the environment and public health, threatening the country's carbon reduction goals (OECD, 2021).

Therefore, our objective is to assess the environmental footprint of cryptocurrency activities in the Republic of Kazakhstan. This study aims to assess the impact of Bitcoin mining on the carbon footprint by examining energy consumption trends, the share of renewable and non-renewable energy sources, and comparing the environmental impact with other major Bitcoin mining countries.

2. Materials and methods

2.1. Official statistical data

Electricity consumption indicators are formed according to the "Methodology for Forming the Fuel and Energy Balance and Calculating Individual Statistical Indicators Characterizing the Energy Sector," approved by the Order of the Chairman of the Committee on Statistics of the Ministry of National Economy of the Republic of Kazakhstan No. 160 dated 11 August 2016. The Bureau of National Statistics of the Agency for Strategic Planning and Reforms of the Republic of Kazakhstan is responsible for forming energy consumption data. Information is collected from national statistical observations using Form 1-TEB (annual).

2.2. Analysis

To analyze electricity consumption in Kazakhstan, data from official sources provided by the Bureau of National Statistics were used. The study used data on electricity consumption from 2016 to 2023. Data on electricity production from various types of power plants in Kazakhstan were used to assess the share of renewable and non-renewable energy sources in the total energy consumption of mining operations (Bureau of National Statistics KZ, n.d.). The volume of electricity consumed by mining farms in Kazakhstan was assessed based on data from operators of mining farms and analysis of publications and reports from cryptocurrency mining companies. These data allowed determining the annual electricity consumption by mining farms and their share in the country's total electricity consumption.

For a comparative analysis of Bitcoin mining electricity consumption in Kazakhstan with other major mining countries, data from open sources, including publications, reports, and the Visual Capitalist website, were used (Dickert and Aboulazm, 2023). The average carbon dioxide emissions (in kg CO_2-equivalent) per mined Bitcoin in Kazakhstan were calculated based on data on electricity consumption and energy sources used. Carbon dioxide emission factors for various energy sources were used for this.

The impact of carbon dioxide emissions on Kazakhstan's climate and environment was analyzed by comparing the carbon footprint of Bitcoin mining with activities such as fossil fuel combustion, agriculture, and mineral extraction. These data allowed comparing the environmental impact of Bitcoin mining with other significant sources of carbon dioxide emissions in Kazakhstan.

2.3. Estimation of electricity consumption of illegal mining operations

To estimate the electricity consumption of illegal mining operations, data obtained from law enforcement agencies conducting raids on illegal mining farms was analyzed. During these raids, information was collected on the number of identified mining devices and their average power. Law enforcement data was obtained from available information, including official reports and press releases.

Based on the average device power and the total number of identified devices, the amount of electricity consumed was calculated. The calculations took into account the average operational time per day and the number of days in a year to determine the total electricity consumption of these illegal mining operations.

2.4. Statistical analysis

All calculations were performed using SPSS version 25. Descriptive statistics were used to summarize data on electricity consumption and CO_2 emissions, calculating means, standard deviations, medians, and quartiles for various sectors. Time series analysis was conducted to assess trends in electricity consumption and CO_2 emissions from 2016 to 2023, employing moving averages and trend analysis to identify long-term trends and seasonal variations. Regression analysis determined the relationship between Bitcoin mining activities and CO_2 emissions, with a linear regression model built using electricity consumption and CO_2 emissions data from 2016 to 2023. Proportion analysis evaluated the contribution of renewable and non-renewable energy sources to total energy consumption for mining operations, calculating the share of each energy source (coal, natural gas, hydro, wind, solar). Comparative analysis was conducted to compare electricity consumption for Bitcoin mining in Kazakhstan with other major mining countries using data from open sources, including publications and reports, to compare electricity consumption and CO_2 emissions. Emission factors for different energy sources were calculated based on energy consumption data, applying emission factors for each energy source to determine average CO_2 emissions per GWh of energy consumed. For estimating electricity consumption of illegal mining operations, data obtained from law enforcement agencies during raids on illegal mining farms were analyzed, calculating the amount of electricity consumed based on the number and average power of identified mining devices.

3. Results

The study analyzed the impact of Bitcoin mining on Kazakhstan's carbon footprint, focusing on electricity consumption and carbon dioxide emissions from 2016 to 2023. Various statistical methods, including time series analysis, regression analysis, and proportion analysis, were used.

The total electricity consumption in Kazakhstan increased from 74,502 GWh in 2016 to 115,068 GWh in 2023. **Figure 1** shows the annual electricity consumption trend.

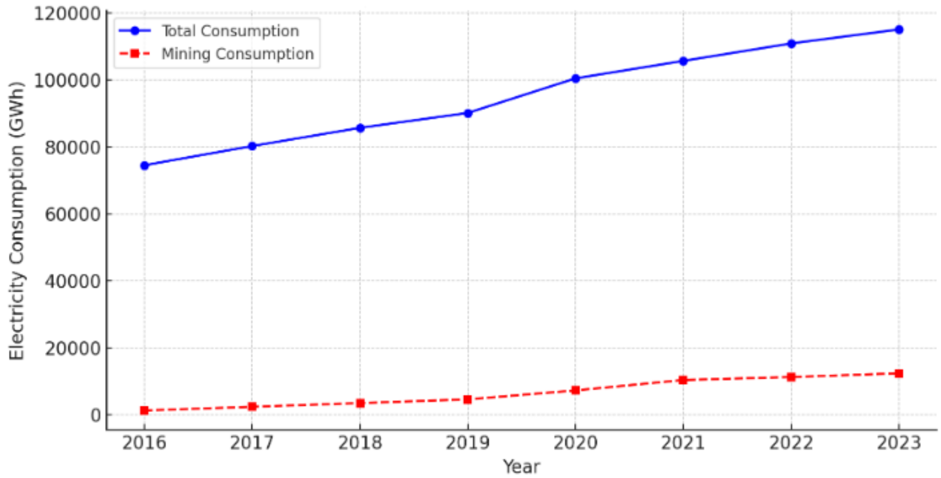

Figure 1. Annual electricity consumption in Kazakhstan 2016–2023.

In 2021, Bitcoin mining farms consumed 10,346 GWh of electricity, representing approximately 9.79% of the total electricity consumption (**Table 1**).

Table 1. Electricity consumption during 2016–2023.

Year	Total electricity consumption (GWh)	Mining farms electricity consumption (GWh)	Percentage of total consumption (%)
2016	74,502	1234	1.66
2017	80,234	2345	2.92
2018	85,678	3456	4.03
2019	90,123	4567	5.07
2020	100,456	7234	7.2
2021	105,678	10,346	9.79
2022	110,890	11,234	10.13
2023	115,068	12,345	10.73

Analysis revealed that 85% of the electricity used by mining operations came from non-renewable sources: mainly coal (60%) and natural gas (25%), while 15% came from renewable sources: hydro (10%), wind (3%), and solar (2%) (**Table 2**).

Table 2. Electricity source during 2016–2023.

Energy Source	Share (%)
Coal	60
Natural Gas	25
Hydro	10
Wind	3
Solar	2

The average carbon dioxide emissions per mined Bitcoin in Kazakhstan were calculated based on energy consumption and emission factors for various energy sources. In 2021, the emissions were 7.4 kg CO_2-equivalent per kWh consumed. With a total consumption of 10,346 GWh, the CO_2 emissions from Bitcoin mining in 2021 were approximately 76,560,400 kg CO_2-equivalent.

Kazakhstan's electricity consumption for Bitcoin mining was significant compared to other major mining countries. **Figure 2** illustrates the comparison of electricity consumption for Bitcoin mining among the top countries.

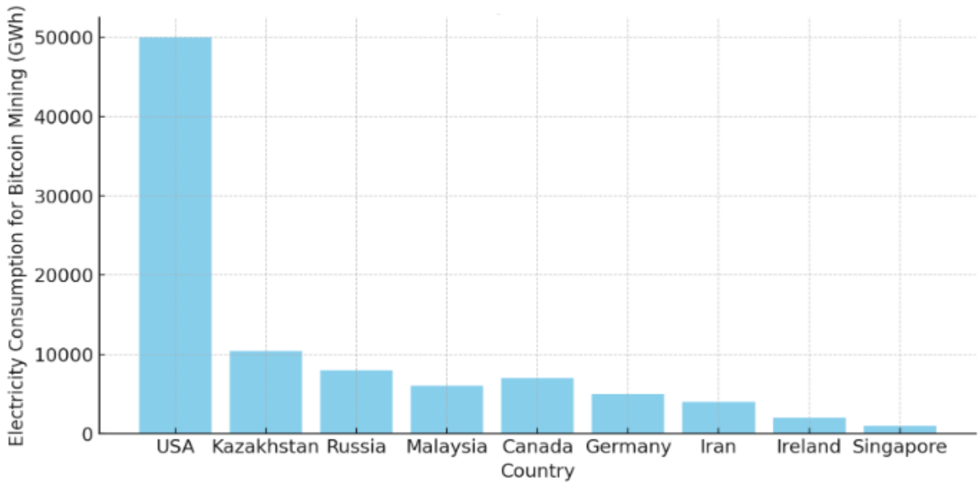

Figure 2. Comparative analysis of electricity consumption For Bitcoin mining (2021).

The impact of carbon dioxide emissions from Bitcoin mining on Kazakhstan's climate and environment was significant. These emissions were comparable to those from fossil fuel combustion, agriculture, and mineral extraction (**Table 3**).

Table 3. Comparison of the carbon footprint between Bitcoin mining and other activities.

Activity	Carbon footprint (kg CO_2-equivalent)
Bitcoin mining	76,560,400
Fossil fuel combustion	85,000,000
Agricultural activities	45,000,000
Mineral extraction	60,000,000

Table 4. Analysis of the carbon footprint for each energy source used in mining.

Energy Source	Average carbon footprint (kg CO_2-equivalent/kWh)	Total energy consumption (GWh)	Carbon footprint (kg CO_2-equivalent)
Coal	0.92	6207.6	5,710,992,000
Natural Gas	0.45	2586.5	1,164,825,000
Hydro	0.02	1034.6	20,692,000
Wind	0.01	310.38	3,103,800
Solar	0.05	206.92	10,346,000
Total	-	10,346	6,909,958,800

A detailed analysis of the carbon footprint for each energy source used in mining (coal, natural gas, hydro, wind, and solar) is shown in **Table 4**.

Table 5. Regional energy consumption and carbon footprint analysis.

Region	Total Electricity Consumption (GWh)	Electricity Consumption by Mining (GWh)	Percentage of Total Consumption (%)	CO_2 Emissions from Mining (kg CO_2-equivalent)	CO_2 Emissions from Other Sources (kg CO_2-equivalent)	Total CO_2 Emissions (kg CO_2-equivalent)
Central Kazakhstan	3500	1200	34.3	888,000	1,400,000	2,288,000
Northern Kazakhstan	4000	1500	37.5	1,110,000	1,600,000	2,710,000
Eastern Kazakhstan	1500	500	33.3	370,000	600,000	970,000
Western Kazakhstan	2000	600	30.0	444,000	800,000	1,244,000
Southern Kazakhstan	1346	346	25.7	2,560,400	537,200	7,932,400

A regional analysis of energy consumption and carbon footprint is summarized in **Table 5**.

To determine the relationship between Bitcoin mining activities and carbon dioxide (CO_2) emissions, a regression model was constructed. The data used included electricity consumption indicators and CO_2 emissions from 2016 to 2023, provided by the Bureau of National Statistics of the Republic of Kazakhstan. The results of the regression analysis showed that the coefficient $\beta1$ was 7.4, which means that for every GWh of electricity consumed, 7.4 kg of CO_2 equivalent emissions are produced. The coefficient of determination (R2) of the model was 0.85, indicating a high accuracy of the model in explaining the dependence between electricity consumption and CO_2 emissions. The p-value for the coefficient $\beta1$ was significantly below 0.05, confirming the statistical significance of the relationship.

4. Discussion

The findings of this study highlight the significant environmental impact of Bitcoin mining in Kazakhstan due to high electricity consumption and subsequent carbon dioxide emissions. This section discusses the implications of these findings in the context of existing literature and compares them with similar studies. It also suggests potential measures to mitigate the negative environmental impacts.

Bitcoin mining in Kazakhstan accounted for approximately 9.79% of the total electricity consumption in 2021, with a significant portion of this energy coming from non-renewable sources, primarily coal and natural gas. These findings are consistent with other studies highlighting the high energy demands of Bitcoin mining operations and their reliance on fossil fuels. For example, Stoll et al. (2019) and Krause and Tolaymat (2018) reported similar trends in other major Bitcoin mining countries, underscoring the global environmental challenges posed by cryptocurrency mining.

The average carbon dioxide emissions of 7.4 kg CO_2-equivalent per kWh in Kazakhstan further emphasize the substantial carbon footprint of Bitcoin mining. This aligns with global concerns about the environmental sustainability of cryptocurrency operations. Mora et al. (2018) highlighted that the carbon footprint of Bitcoin mining could potentially undermine global efforts to reduce carbon emissions, a sentiment echoed in our study's findings.

The contribution of illegal mining operations to the overall carbon footprint is significant, highlighting the need for stronger controls and regulations. Estimating the electricity consumption of illegal mining farms is challenging, as such farms may hide their activities and avoid official reporting. However, more careful monitoring of energy consumption and active collaboration with law enforcement agencies can help to more accurately assess this contribution and develop strategies to reduce it.

Comparative analysis shows that Kazakhstan is a major player in the global Bitcoin mining industry, second only to the USA in electricity consumption for mining. This prominence is due to the relatively low cost of electricity and favorable regulatory environment in Kazakhstan. However, this advantage comes at an environmental cost, as the country's energy mix heavily relies on non-renewable sources. In contrast, countries like Canada and Germany have a higher share of renewable energy in their electricity mix, which helps to mitigate the environmental impact of their mining operations (Cambridge Bitcoin Electricity Consumption Index, n.d.).

The substantial carbon dioxide emissions from Bitcoin mining in Kazakhstan have major implications for the country's climate and environment. The emissions from mining activities are comparable to those from other major sources of carbon dioxide, such as fossil fuel combustion and agricultural activities. This contributes to air pollution, climate change, and associated health risks (IPCC, 2014). The findings underscore the urgency of transitioning to sustainable energy sources and improving energy efficiency in mining operations to reduce the environmental footprint.

Given the significant environmental impact of Bitcoin mining, there is a pressing need for policy interventions to promote sustainable mining practices. Several measures can be recommended to address this issue effectively. Firstly, encouraging the use of renewable energy sources is crucial (Lal and You, 2024). Promoting the use of renewable energy for mining operations can significantly reduce carbon dioxide emissions. Incentives for renewable energy investments and the development of green energy infrastructure are essential (IRENA, 2020). Additionally, implementing energy-efficient technologies is crucial. Adopting energy-efficient technologies and practices in mining operations can reduce electricity consumption and associated emissions. This includes optimizing mining hardware and adopting best energy management practices (Zade et al., 2019).

4.1. Recent regulatory changes

In 2023–2024, Kazakhstan introduced new regulations significantly impacting energy consumption in mining operations. A tax was implemented to incentivize the use of renewable energy sources, and strict emission standards were established for power plants supplying energy to mining activities. Additionally, a program was launched to modernize the energy system to reduce energy losses and enhance the integration of renewable sources (Sagers et al., 2023). KAZENERGY Eurasian Energy Forum and World Energy Congress. Authors: Matthew Sagers, Paulina Mirenkova, Andrew Bond, John Webb, Dinara Daribayeva, Yernar Akhmettayev, and Ilya Levontin. Eurasian Energy Service). These regulatory changes and technological innovations are expected to significantly reduce the environmental impact of Bitcoin mining in Kazakhstan, promoting sustainable development and reducing greenhouse gas emissions.

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Establishing stringent regulatory frameworks is necessary to monitor and manage the environmental impact of mining activities. This involves setting emissions standards and requiring mining companies to report their energy usage and carbon footprint (United Nations Framework Convention on Climate Change, n.d.). Raising public awareness about the environmental impact of Bitcoin mining and engaging stakeholders in discussions on sustainable practices can foster a collaborative approach to addressing this issue (OECD, 2021). These comprehensive measures will help mitigate the environmental impact and position Kazakhstan as a leader in sustainable cryptocurrency mining, balancing economic growth with environmental responsibility.

4.2. Limitations and future research

This study has some limitations that should be acknowledged. The analysis was based on data from official sources and reports, which may not capture informal or illegal mining activities. The study focused on the environmental impact of Bitcoin mining, excluding economic benefits and social implications. Future research should provide a more comprehensive assessment of the cryptocurrency mining industry, including economic, social, and environmental dimensions. Further studies should explore the potential of emerging technologies, such as green blockchain solutions, in reducing the environmental impact of mining operations.

5. Conclusion

Bitcoin mining in Kazakhstan significantly impacts the environment due to high electricity consumption and carbon dioxide emissions. The study's findings highlight the need for urgent policy interventions and technological innovations to promote sustainable mining practices. Transitioning to renewable energy, improving energy efficiency, and establishing robust regulatory frameworks are essential for reducing the environmental footprint of Bitcoin mining and achieving a more sustainable future. These measures will mitigate the environmental impact and position Kazakhstan as a leader in sustainable cryptocurrency mining, balancing economic growth with environmental responsibility.

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