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Evaluating the environmental effects of bitcoin mining on energy and water use in the context of energy transition

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This study investigates the impact of Bitcoin's energy and water consumption on environmental sustainability, focusing on the load capacity factor (LCF) and the roles of energy transition green technology in major cryptocurrency-producing nations. Utilizing the method of moments quantile regression (MMQR) approach, the findings reveal a negative impact of mining energy consumption on environmental sustainability, particularly in the lower quantiles, with a stronger negative effect in the higher quantiles. Energy transition plays a critical role in moderating this impact, though the shift towards cleaner energy sources has not been sufficient to mitigate the adverse environmental effects. The water footprint has limited influence on LCF across upper and lower quantiles. Moreover, the results do not support the LCF hypothesis. An increase in mining activity leads to a rise in LCF, while this effect turns negative in the 90th quantile. These findings underscore the importance of energy transition in reducing Bitcoin's environmental footprint and emphasize the need for policymakers to swiftly enact regulations and foster innovative technologies to promote environmentally sustainable digital currencies while providing valuable insights into water resource management.

Keywords Energy consumption, Mining, Water usage, Sustainable development, MMQR

In the recent decade, the prices of popular cryptocurrencies have grown enormously. Over time, the global trading volume and the frequency of transactions have risen significantly. Across the globe, some major companies have declared that they will turn major parts of their assets into cryptocurrency (CRYT). As a popular type of cryptocurrency, Bitcoin (BTC) is acceptable as a payment mode. Such processes are building trust and attention in the growing CRYT market. There are around one million miners across the world who mine cryptocurrencies[1]. The mining of cryptocurrencies is a rigorous process that utilizes specialized machines to generate newer transactions. This is stored as digital blocks through a blockchain. The growing computational power needed to mine CRYT requires substantial electricity[2]. The study by Krause and Tolaymat[3] documented that mining of Ethereum, Monero, BTC, and Litecoin alone consumed around seventeen thousand seven hundred and fourteen megajoules to create one USD value covering the period January 1, 2016 to June 30, 2018. The mining of BTC leads to 0.6 per cent of global electricity consumption[4]. Thus, the rising demand for energy for CRYT mining has created uneasiness about the effect on this form of currency's environmental sustainability (ES)[5].

Thus, BTC's mining process and operations, which have a large market share, utilize massive energy[6]. The mining process needs ample electricity to power specialized computers that apply proof of work accord algorithm to substantiate transactions that are available in the published ledger on a transaction. It is calculated that about 1 million BTC miners are in operation globally[7]. The study by Krause[8] documented how the mining procedure of CRYT is concomitant with environmental dilapidation. The research indicates that during January 2016, 1005

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kilowatt hours of energy were required to mine one BTC. During 2018 (June), the energy required was 60,461 kilowatt hours. The studies by[9,10] argue that the mining and trading operations of BTC require a considerable amount of energy. Although the energy GDP nexus has been widely explored[11], the nuanced understanding of the mining mechanism of BTC and the amount of electricity consumed is a very intriguing topic for exploration.

The BTC miners require water in addition to electricity. The water is used in two major ways[12]. The first step includes direct water usage for cooling the systems. Water use is related to the types of cooling systems and the local climatic conditions. The second step includes how the miners use water consumption to generate electricity. Water consumption is not widely explored in research related to BTC mining. Research is needed to explore BTC's expanding water footprint against water scarcity. For example, according to the study by de Vries, Kazakhstan alone utilized a 997.9 gl water footprint in 2021. This would lead to a water shortage of about 75 gl by 2030. Again, BTC mining could lead to freshwater conflicts due to strain on water resources.

If CRYT gradually replaces the mainstream currency, exploring the broader implications of this transformation, particularly its association with the environment, is essential[13]. This study explores the effect of BTC mining and water footprint on ES, considering the Load Capacity Curve (LCC), one of the top CRYT footprint nations. In addition, GDP, energy transition, and environmental patents are used as control variables. Our paper contributes to the extant literature by being the first empirical study that analyzes the impact of BTC mining on ES. This research makes a fourfold contribution to the extant seam of literature. First, this is the first study to explore BTC's energy consumption (EC) and water footprint on load capacity sustainability.

Second, we address whether BTCs can serve the broader goal of Sustainable Development (7,13 and 17goals). The 7 and 13 SDGs focThe 17 Sustainable Development Goals aim to end poverty and major deprivations whilethe potential of wealth accumulated from cryptocurrency trading in contributing to the achievement of the United Nations' SDG 7, which that focuses on ensuring affordable and clean energy, and SDG 13, which is centered around taking action to combat climate change. They are aligned to enhance health and education, foster GDP, address climate change issues, and preserve our forests and oceans (UN, 2018). Technological innovation and product specialization can boost Sustainable development[14]. We address the set of Sustainable development goals associated with various dimensions of ES[15]. Our study develops a comprehensive understanding of the effect of BTCs on environment-related Sustainable development Goals. Third, our empirical estimation of BTC mining and its impact on the environment unpacks a series of policy suggestions for the top 10 countries on BTC miners in terms of electricity use and water usage. We advocate urgent policy intervention and technological upgrades to mitigate the major environmental injustice of BTC mining.

Fourth, our study has a methodological add-on in the extant literature. We employ the novel econometric estimation technique on quantiles via moments developed by[16]. The MMQR represents a methodological advancement that circumvents constraints in mean-based research. The adoption of the method of moments quantile regression is pertinent for exploring the heterogeneity of the influence exerted by regressors on target variables.

Our study documents interesting findings. The empirical findings demonstrate that BTC mining positively impacts the LCFat in the lower quantiles. However, it has a negative effect in the medium and upper quantiles. Again, the same trend is noticeable for BTC's water footprint. In contrast, the TGP demonstrate a limited negative effect. It approaches zero effect in the extreme upper quantile.

The remainder of this paper is organized as follows: "Literature review" section reviews the relevant literature. "Methodology and data" section comprehensively explains the technique, variables, and methodology employed in the study. The results and discussion are presented in "Results and discussion" section. Finally, "Conclusion and policy implications" section concludes the study by offering suggested implications.

Literature review

There is a strong possibility that BTCs can potentially supersede the functioning of fiat currencies as the governments across the countries adopt safety measures of BTC against profane plays[17,18]. The usage and adoption of BTC have grown rapidly across the globe. Regarding investment opportunities, BTCs act as hedgers against other asset classes[19]. Arguably, the study by Bouri et al.[20] observed that after the crash in 2013, BTCs acted as diversifiers. A fistful of literature considers the role of CRYP as an alternative to investment in gold in hedging against stocks[21].

Again, BTC acts as a hedger in developing economies but is a diversifier in advanced nations. Arguably, there is a wide-ranging discussion about the fluctuations aspects across BTC and other assets, such as bonds and BTCs[22]; energy commodities and BTCs[23]. In sum, BTCs demonstrate characteristics for financial investment[24], exhibiting hedging and speculation traits[25]. It may be argued that though the discussion on the functions of BTCs in the financial world is well documented, the literature's explorations from the ES perspective are missing.

The CRYT market is still maturing, so more investors are attracted. It is becoming a billion dollars in the capitalization market. At the same time, there has also been an increase in the number of BTC miners. BTC miners are attracted to the high profit rates. It must be mentioned that the energy expenditure on mining is far less than the profits that can be plowed back into BTC[26]. This feature has sought the attention of a greater number of investors to participate in the mining process. However, there are serious environmental concerns as the levels of energy use rise. Further, the increase in mining is generating higher levels of electronic waste. There are other shortcomings, for example, low depreciation and successive frequency of the BTC mining network[27].

Using energy in mining BTCs is crucial and is increasing at a disquieting rate. In a study by[28] it was obtained that power consumption owing to BTC during 2020 was around 120 gigawatts per second. A study by Li et al.[2] documents that CRYT and blockchain technology adversely affect sustainability development. Unarguably, the study by Schinckus et al.[29] documents, based on the autoregressive distributed lag model, that trading CRYT in the short run and long run positively impacts energy consumption. Such processes have adverse implications on the environment.

The level of EC in BTC mining is comparable to the total EC of Mexico and Italy. The studies by[30] have explored the impacts of BTC EC on environmental degradation. They obtained asymmetric causal nexus between a positive shock of BTC demand and environmental degradation. Again, the study by Huynh et al.[31] obtained bidirectional causality amid BTC returns and energy consumption. It is reported that a connectedness exists between EC and BTC trading. Based on variance decomposition analysis, they reported that the directional effect from BTC trading volume to EC is higher than the returns in the long run. Thus, the study indicates an urgent need to develop CRYT sustainably to mitigate climate costs. Earlier studies have documented that BTC trade volume increases carbon and energy footprint[32,33]. Thus, the use of renewables and the adoption of energy-efficient mining will reduce BTC's carbon footprint. Zhang et al.[34], using Granger causality across quantiles, crossquantilgrams, and dynamic connectedness, throw valuable insights on the relationship between BTC mining and climate change. The results obtained crucial directional predictability amid the energy use of BTC mining and carbon dioxide emanations. Further, the dynamic connectedness empirical outcomes document that hash rates propel higher spillover effects on carbon di oxide emissions and BTC electricity consumption. The paper argues an urgent need to convert the CRYT market into a climate-friendly one.

Recently, Mohsin et al.[35] explored the empirical outcome of crypto volume, gross domestic product, and energy use on the sustainability of the environment. The study covered the top 20 crypto trader countries. The Vector Error Correction Model confirmed bidirectional causality amid the degradation of the environment and the volume of crypto for the short and the long term. The study argued that crypto trading and energy use adversely affect environmental quality. Similarly, the study by Bejan et al.[36] documented strong connectedness amid BTC price evolution and EC for mining. Xiao et al.[37] explored the carbon footprint of BTC mining in China from 2017 to 2021. The empirical outcomes documented that the mining process generated 77.84 million tons of carbon di oxide in China. It is predicted that future mining of BTCs will lead to 76.40 million tons of carbon di oxide by 2030. The study suggests that the major governments should focus on environmentally friendly technologies to reduce BTC's dependence on fossil energy.

Given the problems discussed above, there is a lack of exploration into the water footprint of BTCs and the electricity consumption of mining BTCs. Further, scant research on how these processes impact the LCF. Therefore, this study discusses how the water footprint of BTCs and the electricity consumption of mining BTCs affect the environment. To add precision to the estimation, the role of energy transition and the availability of environmental patents are used as controls. The empirical outcomes of this exercise could be used to design digital currencies. Further, how the performance of the blockchain impacts the water footprint and energy markets can be gauged. These insights are important for achieving the sustainable development goal on the availability of affordable and clean energy (SDG 7) and the sustainable development goal on climate change (SDG 13).

Methodology and data
Data
The study investigates the effect of CRYT environmental factors, including EC and water footprint, on ES in the top ten crypto footprint countries: China, USA, Canada, Kazakhstan, Russia, Malaysia, Germany, Norway, Iran, and Ireland. This objective is realized by augmenting the LCC hypothesis, including TGP and energy transition. We have quarterly data considering the time frame from Q3 2019 to Q1 2022. The present analysis emphasizes the substantial economic and ecological consequences of BTC mining. This analysis primarily emphasizes the expenses associated with power, specifically set at $0.05 per kilowatt-hour (kWh). It highlights a significant rise of 53.7% in BTC's water usage in 2021 compared to the previous year, indicating the considerable environmental impact it incurs[12]. The rise in energy use can be linked to the substantial computing requirements of BTC mining. As of December 4, 2023, BTC holds a commanding position in the cryptocurrency sector, accounting for 53% of the market share, which is valued at a staggering USD 814 billion (https://coinmarketcap.com/). In order to expand the extensive BTC industry, we have selected BTC due to its unique data on energy use and water footprint[12,38]. Moreover, we have calculated the energy transition based on the percentage of renewable energy, with coal and natural gas representing over 95% of the energy sources[1]. It generates new BTCs by computational calculations and verifying transactions on the blockchain network. The foundational model is formulated as follows:

Model: LCP = (GDP, crypto energy consumption, crypto water footprint, green patent, energy transition).

$$LCP_{it} = \psi_0 + \psi_1 GDP_{it} + \psi_2 GDP^2{}_{it} + \psi_3 WTR_{it} + \psi_4 ELE_{it} + \psi_5 TGP_{it} + \psi_6 ENT_{it} + \vartheta_{it} \quad (1)$$

Where LCP is the load capacity factor, GDP is GDP, WTR is the water CRYT (BTC) footprint, ELE is the BTC electricity consumption, e ENR is the energy transition, and TGP is the total environmental patents. ψ_1 to ψ_6 are the coefficients. Finally, ε^q_t denotes the error term. The LCC hypothesis of the signs of GDP square $\psi_1 = GDP2 > 0$, and the GDP variable is negative $\psi_2 = GDP < 0$[39,40]. An expected negative effect of BTC's EC and water footprint indicates that the latter also decreases when the environmental BTC increases. On the contrary, a positive impact is anticipated for the environmental patent and energy transition, suggesting that as the prevalence of ENT and TGP increase, the prevalence of ES measured by the LCFwill continue to rise[41–43]. We have presented the logarithmic transformation in Fig. 1, and the descriptive data and sources are shown in Table 1.

Methodology
The MMQR approach

We implemented Machado's MM-QR model, which has widespread use in econometrics studies[44–46]. The MM-QR approach is advantageous for panel data analysis when the objective is to investigate the influence of changes

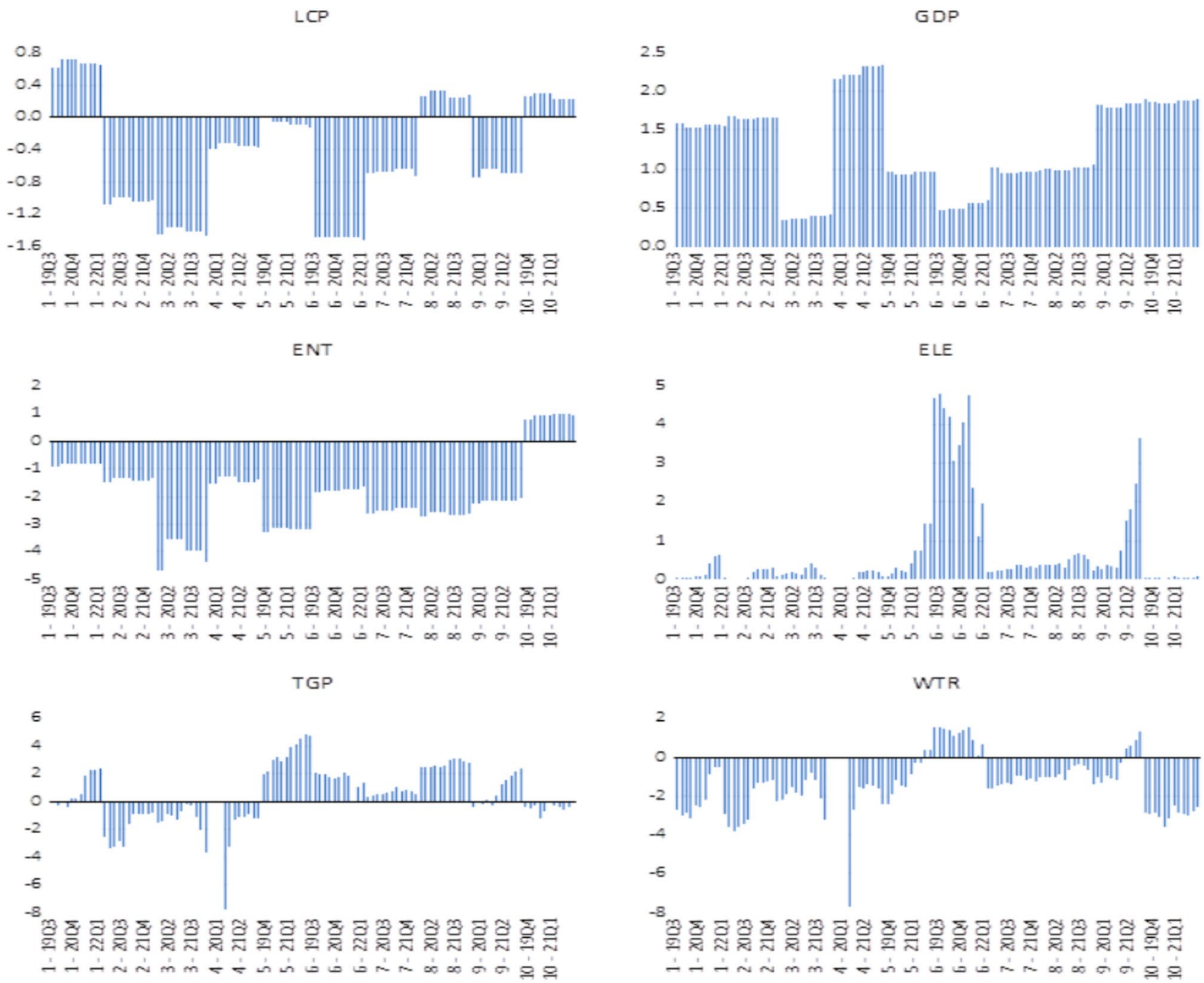

Fig. 1. Data trend.

Variables	Acronym	Measurement unit	Source
Load capacity factor	LCP	$\frac{\text{Biocapacity}}{\text{Ecological footprint}}$ (per capita)	Footprint Network (2023) www.footprintnetwork.org
Economic growth	GDP	GDP prt capita (US $/ constant 2017)	WDI (2023)
Crypto energy consumption	ELE	0.05 USD per kilowatt-hour of electricity (BTC)	The Cambridge Centre for Alternative Finance (CCAF) https://ccaf.io/cbnsi/cbeci.
Crypto water footprint	WTR	Gigaliter (BTC)	[12]
Total envirемental patents	TGP	Total envirемental patents	OECD (2023)
Energy transition	ENT	Renewable energy / (coal + Natural Gas) KWH per capita	Our world in data (2023)

Table 1. Variables description.

in one or more explanatory variables on different percentiles of the response variable[16]. introduced this approach as a substitute for conventional regression techniques like OLS, which may not fully represent the connection between variables. The MM-QR method accurately handles non-normally distributed data or datasets with outliers. Additionally, it provides a more detailed knowledge of how explanatory factors affect different aspects of the dependent one[47,48]. The main benefit of Machado and Silva's regression over current quantile approaches is based on additive fixed effects (αi) that supply distribution estimates of the dependent variable αi given Dit. In addition, it permits the use of methods only applicable for estimating conditional means, such as the differentiation of individual effects in panel data models, while presenting evidence on how the regressors affect the entire conditional distribution. The MMQR is more applicable when the model's explanatory variables are endogenous[49].

The MMQR approach is ideal for evaluating how control variables impact the distribution of conditional income inequality due to its ability to manage non-normality and include endogenous explanatory factors and individual impacts. This approach is more rational since it generates regression quantile values that do not intersect.

$$Q_Y\left(\frac{\tau}{X_{it}}\right)=\left(\alpha_i+\delta_i q\left(\tau\right)\right)+X'_{it}\beta+Z'_{it}\beta+Z'_{it}q\left(\tau\right) \quad (2)$$

Where X_{it} represents the independent variables data, $Q_Y\left(\frac{\tau}{X_{it}}\right)$ represents the distribution under certain conditions of the LCC hypothesis as a variable depending on quantiles onX_{it}. $\alpha_i+\delta_i q\left(\tau\right)$ Represents a scalar parameter for the fixed impact of a quantile.i. $q\left(\tau\right)$reflects the quantile determined by an optimization procedure:

$$Minimize_q \sum_i \sum_t p_t(R_{it}-Z'_{it}q\left(\tau\right)) \quad (3)$$

The check function is indicated as p_t.:

$$p_t\left(A\right)=\left(\tau-1\right)AI\left\{A<=0\right\}+TAI\{A>0\} \quad (4)$$

The quantile regression model

This research will use the QR method to enhance the robustness of the MM-QR outcomes[50]. the panel QR in 2015 was proposed. Unlike standard regression models, which do not take into consideration and can only estimate the average impact of changing market conditions, QR can provide more robust findings by addressing difficulties including heteroskedasticity, skewness, multicollinearity, and structural breaks[51–53].

Results and discussion

Preliminary tests

This section presents the preliminary findings from the descriptive analysis, as shown in Table 2. In addition to the basic summary statistics, we examine the selected series' non-normality, kurtosis, and skewness. Each series contains 110 observations, confirming that the data form a balanced panel. All variables exhibit negative mean values except GDP. The median values closely align with their corresponding means, showing considerable variation and suggesting potential outliers in the data series. The minimum values for all series, except GDP, are negative, reflecting the volatility experienced in the energy, BTC, and technology markets during various financial crises, including the COVID-19 pandemic and the Russia-Ukraine conflict. The standard deviation values indicate that the data points remain close to the mean across all series. All variables are negatively skewed, with skewness coefficients differing from zero, indicating distribution asymmetry. Furthermore, the kurtosis coefficients show excess kurtosis, as they exceed three, confirming a departure from normal distribution. The Jarque-Bera test results indicate that all series reject the null hypothesis of normality, as evidenced by significant probability values. This suggests that the series does not follow a normal distribution. Consequently, the Jarque-Bera test results support using a quantile-based framework as the most appropriate method for addressing the non-linearity within the data.

Correlation finding

The factors about the top crypto emitter nations identified in this study have been calculated and are displayed in Fig. 2. The elements had a significant positive connection with the blue hue, whereas the red color showed a strong negative correlation. The association of LCP with energy transition and GDP is observed to be positive, with values of around 0.64 and 0.69, respectively. The variable environmental CRYT exhibits a strong negative correlation with sustainability, about 0.92 and − 0.83 for EC and water footprint, respectively—similarly, the correlation of LCP with TGP documents a negative correlation around 0.53 and − 0.36.

	LCP	GDP	ENT	TGP	WTR	ELE
Mean	− 0.445	1.301	− 1.892	0.490	− 1.328	0.662
Median	− 0.515	1.289	− 1.961	0.225	− 1.298	0.225
Maximum	0.723	2.350	0.959	4.814	1.566	4.798
Minimum	− 1.507	0.342	− 4.670	− 7.739	− 7.726	0.000
Std. Dev.	0.702	0.594	1.292	2.006	1.475	1.144
Skewness	− 0.007	− 0.037	0.510	− 0.503	− 0.428	2.531
Kurtosis	1.797	1.801	3.268	4.546	5.054	8.261
J-B	6.638	38.406	182.065	15.585	22.696	242.63
Probability	0.036	0.037	0.078	0.000	0.000	0.000
Observations	110	110	110	110	110	110

Table 2. Descriptive data.

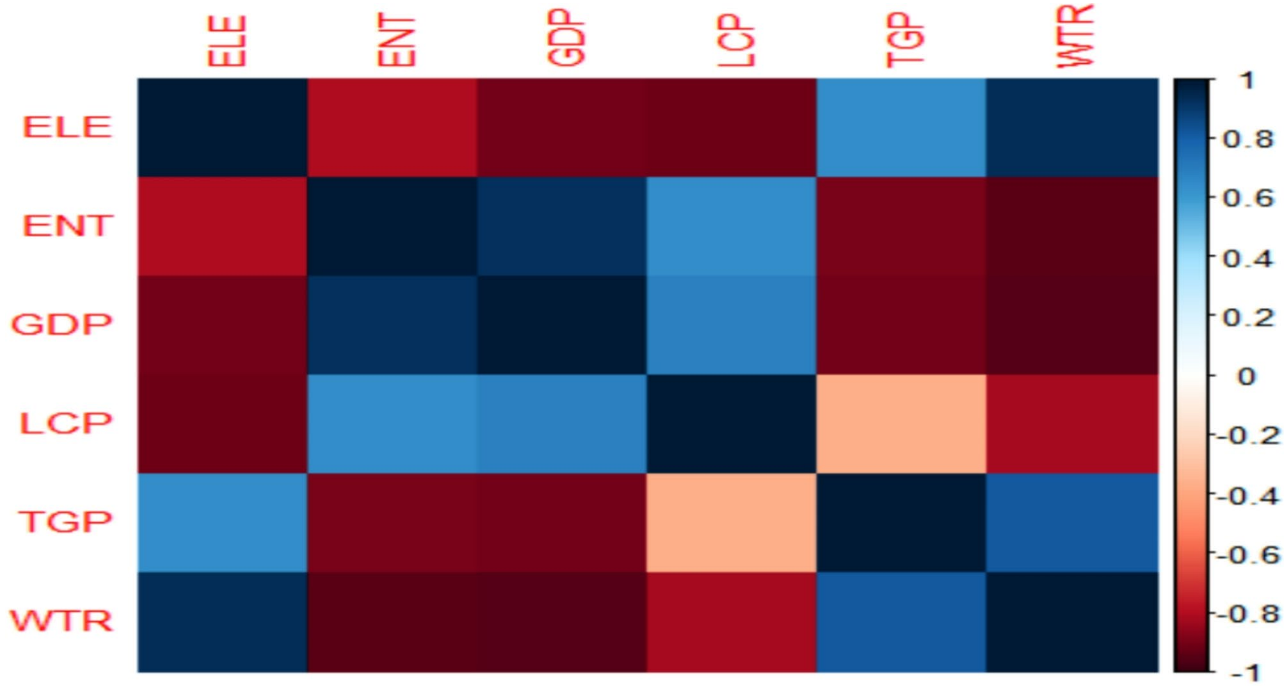

Fig. 2. Correlation matrix.

Test	Test statistics	*p*-value
B-PLM	207.501	0.000
PS LM	17.129	0.000
Pesaran CD	3.114	0.001

Table 3. CSD test results.

CSD findings

Table 3 presents the results of the CSD test. CSD tests whether the effect of crypto mining in one country is observed in other BTC mining rest countries. Since the variables contain CSD, the stationarity of the variables is examined with the[54,55] Pesaran test, which considers CSD in the heterogeneity among variables in the panel data.

MMQR results

Figure 3 illustrates the outcomes of a panel analysis utilizing MMQR. The finding indicates the progressively positive influence of GDP on LCP from the lower quantile to the upper quantile. On the contrary, GDP^2 documents the inverse case of GDP coefficients, indicating the LCC hypothesis's non-validity in the context of BTC's environmental effect. We observe that BTC mining positively affects the LCP in the lower quantiles, but this effect is negative in the medium and upper quantiles. The same trend is noticed for the BTC water footprint and energy transition, albeit with a lesser relative effect and more stability around the mean. Conversely, the green patent exhibits a limited negative effect decrease, approaching no effect (zero) in the extreme upper quantile.

Table 4 displays the more detailed results of a panel analysis utilizing MMQR for various quantiles: lower (10th to 30th), medium (30th to 70th), and higher (70th to 90th) for all variables. The effect of GDP on the LCP demonstrates a substantial impact. The impact in the lower percentile is around 0.75 to 1.79 and becomes increasingly significant at the medium and higher quantiles, about 2.8 and 4.7, respectively. The finding reveals a consistent negative influence of GDP^2 on LCP ranging from − 0.11 at the extremely lower quantile 10th to 1.69 at the upper quantile 90th. In the lower quantiles, BTC mining has a limited effect on LCC. These results reject the LCC hypothesis and accept the EKC theory, which supported the prioritized industrialization and natural resources consumption patterns. The outcomes contradict the prior studies that provided the LCC hypothesis in different countries[39,40].

A 1% increase in ELE resulted in 0.05% increases in LCP; however, this effect becomes negative about − 0.02 and − 0.12 in the 90th. The concentration of mining activities in certain regions can lead to localized environmental stress. This includes not only increased energy consumption but also potential impacts on local ecosystems and water resources. The heat generated by extensive mining operations can further contribute to local environmental changes[56](. Additionally, the electronic waste generated from mining hardware, which has a relatively short lifespan, poses another environmental challenge. As hardware becomes obsolete or wears out, it

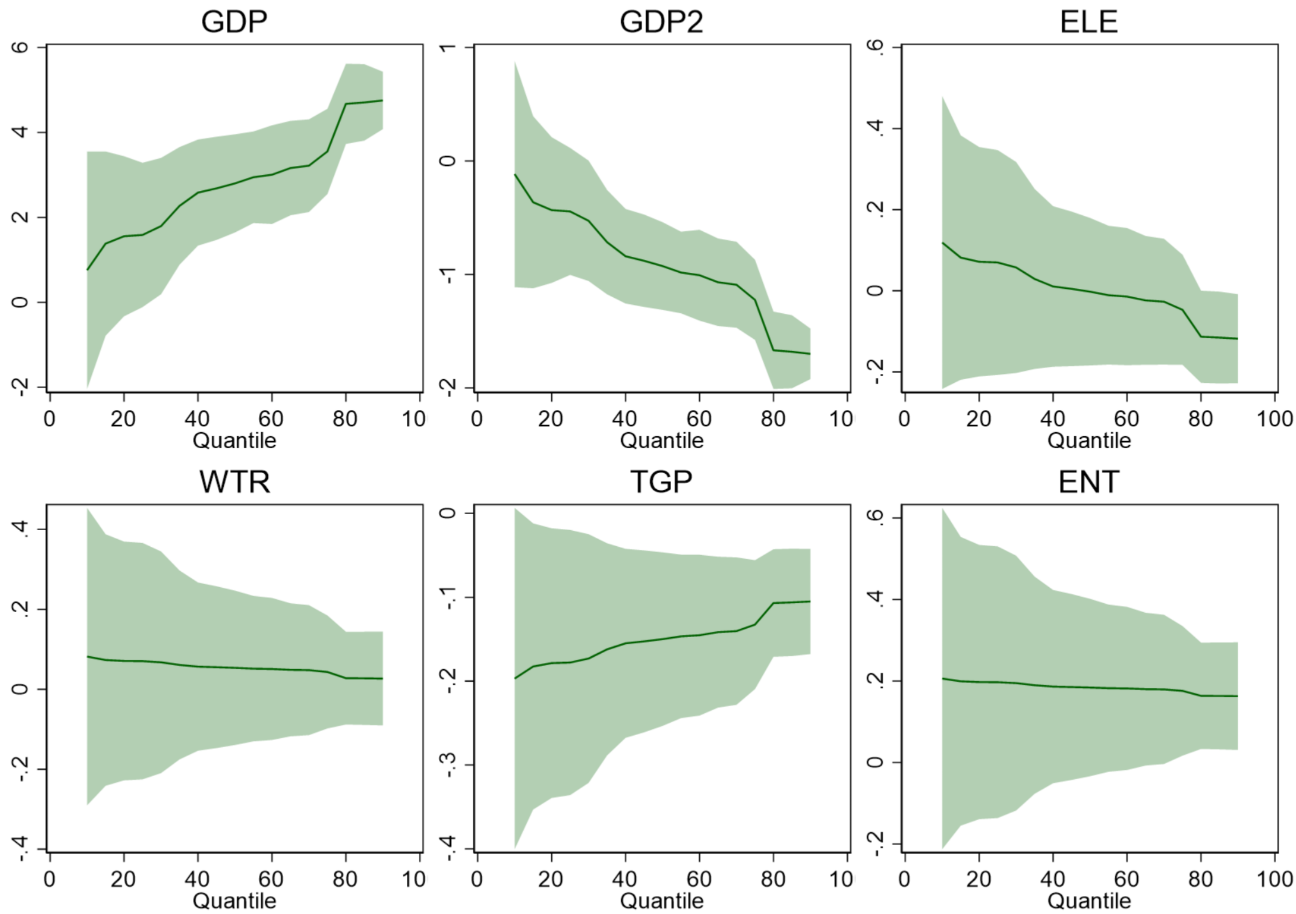

Fig. 3. Method of moments quantile regression results.

contributes to increasing amounts of electronic waste, which can be difficult to recycle and manage sustainably. It is perceptible from the findings that a 1% increase in BTC water footprint increases LCP by 0.08–0.02% from the lower to the upper quantile. the water usage in BTC mining might not be significant enough to raise major sustainability concerns. This could be due to a number of reasons, such as the use of more efficient cooling technologies, reliance on renewable energy sources with lower water footprints. The decrease in effect to 0.02 in the upper quantile could indicate that as the scale of BTC mining increases, the water footprint becomes more significant. This increased water usage might raise concerns about local water resources, especially in regions where water is scarce. Higher levels of water consumption in these regions could lead to conflicts over water resources and exacerbate local environmental issues. The findings corroborate the prior study[12,38]. Nonetheless, this impact diminishes in intensity concerning the green patent. The lower (50th percentile) coefficient is −0.19, marginally increasing to −0.10 at the 90th percentile. This result contradicts the previous studies.REF, which TGP. Some countries examined in this study, such as Iran, Kazakhstan, and Ireland, may impact the limited effectiveness of the green paten effect on LCP. The lower quantiles exhibit a positive effect of 0.2 for the ENT coefficient. As we progress to the middle and upper quantiles, the favorable effect becomes stable, noticeable at about 0.16%.

Robustness test

For checking robustness, we have applied quantile regression. Figure 4; Table 5 show robust findings of MMQR using quantile regression. This outcome corroborates the previous finding regarding the LCC hypothesis's non-validity in the top ten crypto footprints. The results also highlight the limited effect of green paten and energy transition. Environmental footprint BTC, particularly in the upper quantile, is shown to affect ES negatively.

Conclusion and policy implications

Considering the LCC hypothesis, this study investigated the effect of environmental BTC footprint and energy transition in top-emitting from BTC. The results documented a steadily increasing effect of GDP on LCP and a negative effect of GDP[2], indicating the LCC hypothesis does not hold in our examination. It was noted that BTC mining hurts the environment, while the water footprint has a limited effect. Similar patterns can be observed for green patterns and energy transition in the top ten CRYT emitter countries.

Addressing the water footprint of BTC mining requires a comprehensive policy approach that balances the sector's economic benefits with environmental sustainability. Key strategies include regulating the locations of

	Coefficient	Z	P-value
10th			
GDP	0.757	0.53	0.595
GDP2	− 0.115	− 0.23	0.821
ELE	0.119	3.29	0.001
WTR	0.081	2.74	0.006
TGP	− 0.196	− 1.90	0.058
ENT	0.206	− 0.73	0.464
_cons	− 1.73	− 1.42	0.156
30th			
GDP	1.796	2.19	0.028
GDP2	− 0.526	− 1.94	0.052
ELE	0.057	4.00	0.000
WTR	0.067	4.61	0.000
TGP	− 0.173	− 2.29	0.022
ENT	0.194	1.84	0.066
_cons	− 1.927	− 2.15	0.032
50th			
GDP	2.802	4.75	0.000
GDP2	− 0.925	− 4.69	0.000
ELE	− 0.002	− 3.12	0.002
WTR	0.0537	4.09	0.000
TGP	− 0.149	− 2.84	0.005
ENT	0.183	1.66	0.097
_cons	− 2.11	− 3.38	0.001
70th			
GDP	3.219	4.44	0.000
GDP2	− 1.090	5.78	0.000
ELE	− 0.0268	− 5.64	0.000
WTR	0.048	3.12	0.002
TGP	− 0.140	− 3.13	0.002
ENT	0.179	1.92	0.055
_cons	− 2.197	− 4.15	0.000
95th			
GDP	4.756	13.81	0.000
GDP2	− 1.699	− 14.97	0.000
ELE	− 0.118	− 2.11	0.035
WTR	0.0268	0.45	0.653
TGP	− 0.105	− 3.29	0.001
ENT	0.162	2.42	0.016
_cons	− 2.48	− 6.56	0.000

Table 4. Moments quantile regression results.

BTC mining operations should adopted to avoid areas with water scarcity and imposing stringent water usage standards to promote efficient use of water resources. Incentivizing the adoption of renewable energy sources is also crucial, as it indirectly reduces the water footprint by lessening reliance on water-intensive fossil fuel-based power. Additionally, enforcing monitoring and reporting requirements for water usage in mining facilities would enhance transparency and encourage best practices. It should also be supporting research and development aimed at reducing the water footprint, such as improving cooling technologies and exploring alternative mining methods, is equally important. Implementing carbon taxation or cap-and-trade systems could also play a significant role in internalizing the environmental costs associated with BTC mining's carbon emissions, incentivizing a shift towards greener practices. In China and the United States, regulations could incentivize renewable energy adoption through carefully considered subsidies and increased carbon prices with emissions. Canada and Norway, blessed with copious hydroelectric potential, can leverage this natural endowment to offer mining operations cost-competitive, emissions-free energy solutions reinforced by environmental certification and strict compliance monitoring. Kazakhstan and Russia should introduce renewable subsidy schemes and enforce exacting ecological oversight, especially in remote mining zones prone to oversight. Malaysia and Germany could further integrate mining into national renewable drives and establish sector benchmarks for

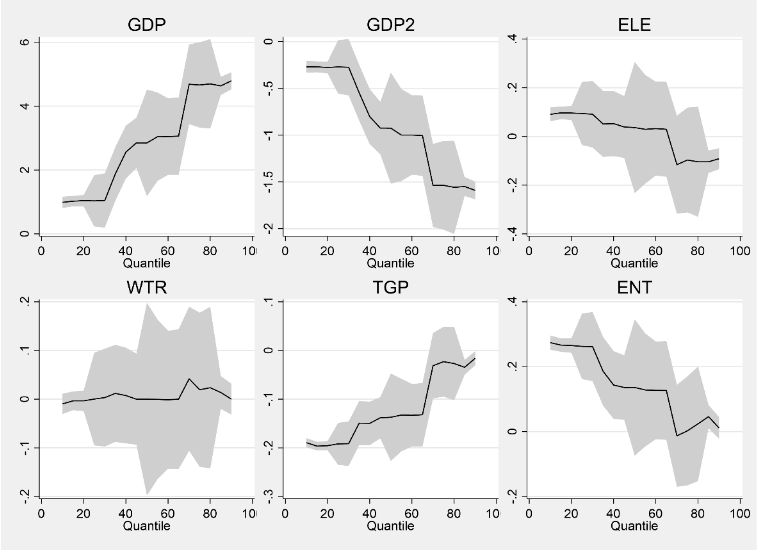

Fig. 4. Quantile regression results.

resource use. Iran may prioritize building renewable facilities to power mines and institute energy rationing during periods of heavy demand. Ireland could champion advanced waste heat reclamation in data centers hosting mining and tender tax relief for operations demonstrating minimal carbon signatures. These nation-specific approaches would facilitate mining's more sustainable conduct while supporting industry growth. There are some limitations of the study. This research only considers the top ten cryptocurrency emitter countries and may not capture global trends, limiting the extent to which the results can be generalized. It also focuses on the water and environmental footprints of Bitcoin mining while overlooking other important direct and indirect pathways of environmental change, such as land use and biodiversity loss. Data limitations regarding both the availability and accuracy of environmental impact data may also affect the reliability of the analysis. We cannot consider possible rapid-level mitigating technological innovations in blockchain technology that could significantly converge on the environmental footprint of cryptocurrency mining. Future research should explore various important paths to deepen understanding and boost mitigation strategies. First, investigating innovative technologies such as proof-of-stake blockchain mechanisms could highlight potential reductions in energy usage compared to conventional proof-of-work systems. Additionally, expanding studies to involve a broader range of nations with diverse regulatory and technological landscapes would supply a more thorough global perspective. Long-term studies might track the temporal dynamics of environmental impacts, assessing the long-term consequences of technological and policy alterations. Analyzing the potency of specific regulatory policies, such as carbon taxes and renewable energy incentives, would also be crucial in judging their real-world efficacy. Moreover, adopting interdisciplinary approaches integrating economics, environmental science, and technology could offer more holistic insights into the impacts and solutions for digital currency mining's environmental footprint. Lastly, developing precise measures for quantifying energy consumption and understanding the more extensive socio-economic repercussions, like effects on local communities and energy prices, would contribute to more informed policymaking and community involvement.

	Coefficient	Z	P-value
10th			
GDP	0.988	11.12	0.000
GDP2	− 0.269	− 8.53	0.000
ELE	0.091	6.36	0.000
WTR	− 0.009	− 3.91	0.001
TGP	− 0.189	− 39.65	0.000
ENT	0.274	24.53	0.000
_cons	− 1.452	− 18.00	0.000
30th			
GDP	1.045	2.44	0.016
GDP2	− 0.274	− 1.81	0.074
ELE	0.091	3.15	0.002
WTR	0.003	2.34	0.021
TGP	− 0.191	− 8.33	0.000
ENT	0.262	4.87	0.000
_cons	− 1.497	− 3.85	0.000
50th			
GDP	2.849	3.38	0.001
GDP2	− 0.925	− 3.09	0.003
ELE	0.0366	3.51	0.001
WTR	2.09e-06	2.70	0.008
TGP	− 0.137	− 3.03	0.003
ENT	0.136	1.28	0.202
_cons	− 2.31	− 3.03	0.003
70th			
GDP	4.60	6.83	0.000
GDP2	− 1.56	− 6.54	0.000
ELE	0.0024	0.61	0.543
WTR	− 0.125	− 1.78	0.077
TGP	− 0.002	− 0.03	0.979
ENT	− 0.005	− 1.39	0.167
_cons	− 2.84	− 5.34	0.000
90th			
GDP	4.68	7.44	0.000
GDP2	− 1.537	− 6.88	0.000
ELE	− 0.115	− 2.99	0.003
WTR	0.041	8.43	0.000
TGP	− 0.031	− 3.09	0.002
ENT	− 0.012	− 9.55	0.000
_cons	− 2.94	− 5.15	0.000

Table 5. Quantile regression results.

Data availability

Data will be available on request from the corresponding author.

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Declarations

Competing interests

The authors declare no competing interests.

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