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OPPORTUNITIES TO IMPROVE ENVIRONMENTAL SUSTAINABILITY AND INTEGRATE ENVIRONMENTAL STANDARDS TO REDUCE THE ENVIRONMENTAL IMPACT OF CRYPTOCURRENCY INDUSTRY DEVELOPMENT

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ABSTRACT

The cryptocurrency industry creates a significant environmental burden, consuming 0.61-0.78% of global electricity and generating 0.28% of global carbon dioxide emissions. The purpose of the study was to identify opportunities to increase environmental sustainability and integrate environmental standards to reduce the burden on the environment from the development of the crypto industry. The study used a qualitative methodological approach combining a systematic comparative analysis of regulatory documents of eight jurisdictions for the period of 2022-2025 and semi-structured expert interviews. The jurisdictions were classified according to the degree of regulation: strict (EU, Switzerland), moderate (USA, Great Britain, Japan), liberal (Singapore, UAE), and prohibitive (China). The results demonstrated substantial heterogeneity in regulatory approaches with different environmental impacts. Information and fiscal mechanisms have the greatest potential to achieve environmental sustainability while minimizing unintended consequences. Prohibitive approaches create mixed consequences for the environment, increasing global emissions by 15-20% due to the migration of mining to regions with more carbon-intensive energy. The study demonstrates the need for international coordination of regulatory efforts and a shift from prohibitive to transformative strategies. The proposed three-level strategy for the integration of environmental standards (mandatory reporting, economic incentives through differentiated taxation, and progressive mandatory standards) shows the potential to reduce the environmental burden from the development of the crypto industry.

Keywords: cryptomining, environmental sustainability, green economy, carbon emissions, international coordination.

INTRODUCTION

Over the past decade, the cryptocurrency industry has transformed the global financial system (Abdullayev I. et al., 2024; Abdullayev R. et al., 2024; Shakhov et al., 2025), but the energy-intensive nature of the cryptocurrency mining process has drawn close attention to its environmental consequences.

The environmental impact of cryptomining poses a serious challenge not only to environmental activists but also to institutional regulators. Blockchain technology presents an innovative fiscal instrument influencing the transformation of the global economy (Kirillova et al., 2023; Safiullin et al., 2025). At the same time, mining, as part of the crypto industry, consumes a lot of electricity. Increased energy consumption often leads to increased greenhouse gas emissions, which belies international climate commitments (Krasnikov and Mironov, 2024).

First, cryptomining presents a significant environmental burden at the global level. According to systematic estimates, in 2021-2023, the global industry consumed 0.61-0.78% of global electricity, which is equivalent to the energy consumption of Malaysia, while generating about 106 million tons of CO_2 emissions, or 0.28% of global emissions (Hebous & Vernon, 2023). Predictive models foresee a potential increase in these indicators: without regulatory pressure on miners, the energy consumption of the Bitcoin blockchain could peak at 296.59 TWh by 2024, generating 130.50 million metric tons of carbon emissions (Jiang et al., 2021). Interdisciplinary research, including direct measurements of emissions at the level of individual mining enterprises, reveals high elasticity of electricity production in relation to the price of cryptocurrencies (Papp et al., 2023), which emphasizes the complexity of forecasting (Shakhov et al., 2025) and regulating the environmental impact of this industry.

Second, the data centers that service cryptocurrency exchanges and blockchain infrastructure are an additional source of environmental burden. Studies show that the infrastructure for storing and processing transactions, including cloud services and validator nodes, consumes significant amounts of electricity to cool server equipment and ensure the uninterrupted operation of systems (Siddik et al., 2021). Data centers serving large cryptocurrency exchanges generate substantial carbon emissions, especially in regions generating a high share of carbon (Hebous and Vernon-Lin, 2024; Krasnikov and Mironov, 2024). The combined impact of mining and supporting infrastructure amplifies the need for a comprehensive regulatory approach to environmental sustainability across the crypto industry (Volosova, 2024; Zharova, 2024).

The problem is exacerbated by the lack of a unified international approach. Different jurisdictions apply diametrically opposed strategies – from a complete ban to the provision of tax breaks (Balanyuk and Gurko, 2023; Okishev, 2024).

Research questions:

- What are the main differences between regulatory approaches to the environmental regulation of cryptomining?
- What regulatory tools prove the most effective at achieving environmental sustainability?
- How do regulatory differences affect success in achieving environmental sustainability and reducing global emissions?.

Literature Review

Regulatory Approaches: From Complex Requirements to Complete Bans

The international landscape of crypto mining regulation is marked by significant heterogeneity of approaches. The European Union is implementing an integration strategy through the Markets in Crypto-Assets Regulation (MiCA), which entered into force in June 2023 and establishes uniform rules for crypto assets throughout the EU (The European Parliament and the Council of the European Union, 2023). Central to the European approach is the mandatory disclosure of the negative environmental impact of consensus mechanisms for both crypto asset issuers and crypto service providers, which has been a requirement since 30 December 2024 (European Securities and Markets Authority (ESMA), 2024; Petrov et al., 2024). Although a complete ban on the most energy-intensive consensus mechanism, the proof-of-work (PoW, blockchain network protection mechanism) used by Bitcoin and other cryptocurrencies, has not been imposed, European legislators have ruled that any adverse impacts of consensus mechanisms on the climate must be properly identified and disclosed (Berger and Kalokyris, 2023).

The North American approach is distinguished by the fragmentation of regulation between the federal and regional levels. At the federal level, the USA proposed the DAME tax, which is planned to be introduced in phases over three

years: 10% of the cost of electricity in the first year, 20% in the second, and 30% in subsequent years (Hebous and Vernon, 2023). At the level of states, the dynamic is diametrically opposite: New York has imposed a two-year moratorium on new PoW operations using non-renewable energy sources, while Montana has passed a crypto-friendly law prohibiting local authorities from restricting mining (Hwang et al., 2023). Asian jurisdictions use polar models of regulation. China has adopted the most restrictive approach, introducing a complete ban on cryptomining in 2021, motivated by environmental and energy considerations (Carreras, 2024). Kazakhstan implemented a fiscal approach in 2022, introducing an electricity tax for crypto miners in the amount of $0.002-0.056 per kWh (Hebous and Vernon, 2023). Regulatory diversity creates contradictory effects on the achievement of the Sustainable Development Goals (SDGs) articulated in the UN 2030 Agenda. On the one hand, strict environmental requirements in individual jurisdictions stimulate technological innovation and the transition to renewable energy sources (RES), which agrees with Goal 7 (Affordable and Clean Energy) and Goal 13 (Climate Action). Mandatory sustainability reporting requirements enhance industry transparency and stakeholder awareness, consistent with Goal 12 (Responsible Production and Consumption). Fiscal tools such as environmental taxes create economic incentives to reduce carbon footprint and can generate revenue to finance climate programs. On the other hand, in the absence of international coordination, miners migrate to less heavily regulated jurisdictions, potentially increasing global emissions and undermining individual countries' decarbonization efforts. This dynamic creates the risk of a race to the bottom in environmental standards, with jurisdictions competing to attract the crypto business by easing environmental requirements. Thus, local regulatory successes can be offset by the global redistribution of environmental damage, impeding the achievement of systemic SDGs.
The present study seeks to fill these gaps with a structured comparison of regulatory approaches across eight jurisdictions with a focus on the environmental effectiveness of different regulatory tools.

MATERIAL AND METHODS

Methods

Study Design. The study uses a qualitative methodological approach combining two complementary methods: a systematic comparative analysis of regulatory documents and semi-structured expert interviews (2025, 10 experts). This design allows, on the one hand, to identify formal differences in regulatory requirements through the analysis of official documents and, on the other hand, to deepen the understanding of the logic behind regulatory decisions and assess their practical effectiveness with a comprehensive understanding of regulatory approaches to the environmental regulation of cryptomining and their potential impact on achieving SDGs.
For comparative analysis, we selected eight jurisdictions grouped by the severity of regulation (Table 1).

Table 1. Classification of jurisdictions by the severity of environmental regulation of cryptomining.

Group	Degree of regulation	Jurisdictions	Characteristics of the environmental regulation approach
A	Strict	EU, Switzerland	Mandatory sustainability disclosure (MiCA), comprehensive environmental reporting requirements
B	Moderate	USA (federal + states: New York, Texas, Montana), Great Britain, Japan	Fragmented regulation, evolving requirements, differences between federal and regional levels
C	Liberal	Singapore, UAE (Dubai)	Minimum environmental requirements, support for innovation, crypto business involvement
D	Prohibitive	China	Complete ban on cryptomining (2021) motivated by environmental and energy considerations

The analyzed jurisdictions were chosen based on the following criteria. The first criterion was significance in the context of global cryptomining: the jurisdictions included in the analysis collectively represent various regulatory models and cover approximately 68-72% of identifiable global mining activity according to the Cambridge Center for Alternative Finance (2024). The second criterion was the presence of formalized environmental regulation or its explicit absence. The third criterion was the variety of regulatory tools: the representation of various types of intervention, including mandatory disclosure of information, environmental taxation, moratoriums, prohibitions, and liberal approaches. The fourth criterion was the availability of primary regulatory documents in English or in a professional translation to ensure the reliability of content analysis. Through these criteria, we formed a sample of eight jurisdictions that ensured the methodological validity of the comparative analysis while keeping the study

manageable. The analysis of regulatory documents was systematic and covered the legislation of each of the eight jurisdictions for the period of 2022-2025. The body of analyzed documents consisted of the following categories of sources: legislative acts (regulations, laws, and regulations establishing formal requirements for cryptomining activities, including disclosure obligations, environmental taxes, interpretative documents of financial regulators, licensing requirements agencies, and prohibitions); guidelines of national environmental regulators and central banks detailing the application of legislative norms to the crypto industry; and consulting documents.
Expert interviews. To assess the practical effectiveness of the approaches, semi-structured expert interviews were conducted with representatives of key stakeholders (N = 10). Expert selection criteria included professional experience in crypto-asset regulation or environmental practice (minimum 5 years). The sample consisted of the representatives of national regulators (n = 3), the industry (n = 3), the academic community (n = 2), and international sustainable development organizations (n = 2). The interview protocol covered the following thematic blocks: (1) factors determining the choice of regulatory tools in various jurisdictions; (2) assessment of the environmental effectiveness of existing approaches; (3) barriers to international regulatory coordination; (4) predictive estimates of the reduction of environmental burden from the development of the crypto industry.
Data analysis focused solely on the environmental implications of regulatory approaches. The coding of documents and interviews aimed to identify causal relationships between the types of regulatory instruments and their potential or actual impact on reducing the energy consumption and carbon emissions of cryptomining. The economic, legal, and technological aspects of regulation were considered solely to the extent that they determine the environmental effectiveness of regulatory approaches.

RESULTS

Diversity of Regulatory Instruments

The analysis of regulatory documents has identified five main types of regulatory tools (Table 2).

Table 2. Comparative analysis of regulatory instruments for the environmental regulation of cryptocurrency mining.

Jurisdiction	Key regulatory instruments	Implementation status	Enforcement mechanisms	Timeframe
EU	Mandatory disclosure of information on the environmental impact of consensus mechanisms (MiCA, article 59); ESG reporting requirements	Mandatory (since 30.12.2024)	Administrative sanctions, license revocation	Permanent
Switzerland	Integration into the existing fiscal regulation system; carbon footprint disclosure requirements	Mandatory	FINMA monitoring, sanctions for non-compliance	Permanent
USA (federal)	The proposed DAME tax (10% → 20% → 30% of the cost of electricity); energy efficiency standards	Under discussion	Financial mechanisms (upon adoption)	Gradual introduction over 3 years
USA (New York)	A two-year moratorium on new fossil fuel PoW operations	In effect (until 2024)	Permit issuance ban	2 years (with a possible extension)
USA (Texas)	Demand management programs; incentives for using RES	Voluntary	Economic incentives	Permanent
Great Britain	Consultations on disclosure requirements; inclusion in fiscal regulation	Preparatory stage	Under development	Expected by 2025
Japan	Voluntary industry standards; promoting the use of RES	Largely voluntary	Reputational mechanisms	Permanent
Singapore	Industry self-regulation; voluntary environmental certifications	Voluntary	Market mechanisms	Permanent
UAE (Dubai)	Minimal regulation; focus on attracting investment	No dedicated environmental regulation	None	–
China	A complete ban on cryptomining	Mandatory (since 2021)	Shutdown of operations, administrative measures	Permanent

The potential and actual environmental effectiveness of different regulatory strategies were evaluated based on expert interviews (N = 10) and the analysis of available data (Table 3).

Table 3. Assessment of the environmental effectiveness of regulatory approaches.

Jurisdiction group	Direct impact on emissions	Promotion of the transition to RES	Unintended effects	Expert assessment (N=10)
A: Strict regulation (EU, Switzerland)	Moderate: increased transparency, indirect pressure on operators	High: ESG requirements drive the transition	Risk of regulatory arbitrage within the EU (minimal)	High long-term effectiveness (8/10 experts)
B1: Moderate (fiscal) (USA federal – DAME)	High potential: the tax internalizes externalities	Very high: economically stimulates RES	Risk of migration to other states/countries	Potentially high effectiveness (7/10)
B2: Moderate (moratorium) (New York)	High local: blocks growth based of fossil fuels	Moderate: stimulates only RES-based projects	Significant risk: migration to neighboring states	Limited global effectiveness (4/10)
B3: Moderate (incentives) (Texas, Japan)	Low: voluntary participation limits coverage	Moderate: economically attractive for new projects	Risk of greenwashing without real change	Moderate effectiveness (5/10)
C: Liberal (Singapore, UAE)	Minimal: no mandatory requirements	Low: market mechanisms are insufficient	Attracts high-carbon operations	Low effectiveness (2/10)
D: Prohibitive (China)	Paradoxical effect: locally high, globally negative	None	Negative global consequences: migration to regions with more carbon-intensive energy (an estimated 20% increase in emissions)	Globally counterproductive (9/10)

The analysis identified five key factors defining differences in regulatory approaches.

Key barriers to environmental sustainability (identified by expert interviews):

- Carbon leakage effect: the migration of mining to regions with carbon-intensive energy increases global emissions instead of reducing them (noted by 10/10 experts);
- Lack of international coordination of environmental standards: disparate national measures fail to reduce cumulative climate impacts (9/10 experts);
- Inability to monitor actual carbon footprint: the decentralized nature of operations makes it impossible to verify the use of RES (7/10 experts);
- Environmental standards development lagging behind technological changes: new consensus mechanisms are implemented faster than requirements for their environmental impact are developed (8/10 experts);

Table 4 presents a comparative ranking of regulatory approaches by their potential to promote environmental sustainability.

Table 4. Comparative assessment of the potential of regulatory approaches
to achieve environmental sustainability.

Rank	Regulatory approach	Jurisdictions	Strengths	Limitations	Scalability potential
1	Mandatory disclosure + ESG integration	EU, Switzerland	Creates transparency; minimal migration risk; basis for stricter regulation	Indirect impact; takes a long time to produce effect	High
2	Financial tools (corrective taxation)	USA (DAME – proposed)	Internalizes externalities; economically incentivizes RES; generates revenue	Risk of migration without international coordination; political difficulty	High
3	Economic incentives for RES	Texas, Japan	Stimulates innovation; industry support	Limited coverage; risk of "greenwashing"	Moderate
4	Temporary moratoriums	New York	Quick local effect	Migration to neighboring regions; lack of a systemic solution	Low
5	Voluntary self-regulation	Singapore, UAE, Japan (partially)	Minimal costs; industry flexibility	Insufficient coverage; lack of enforcement	Low
6	Complete ban	China	Local effectiveness	Globally counterproductive; increases global emissions	Very low/negative

Discussion. The central aim of the study was to establish the fundamental contradiction between local rationality and regulatory choice and its global environmental consequences. The results show that the very approach to the environmental regulation of the cross-border crypto industry needs to be reworked. Jurisdictions with a high share of RES (EU > 40%) objectively have the potential to attract low-carbon mining but mainly use information tools with a weak direct impact on emissions. In contrast, jurisdictions with carbon-intensive energy (65% coal in China) apply severe restrictions that push mining to other carbon-intensive regions. As a result, despite a local decline, global emissions are rising (~ 20% increase after the China ban). The interpretation of this phenomenon indicates a critical gap between the territorial logic of regulation and the universal nature of both climate problems and the crypto industry itself. Effective environmental regulation of cryptomining requires not controlling activities on the given territory but rather managing the direction of capital migration on a global scale, thereby reducing the environmental burden of the crypto industry. The second key finding concerns the role of natural conditions for RES as a determinant of potential for environmental transformation. Jurisdictions with abundant renewable resources (Iceland with 100% RES, factor score 10/10) have a natural competitive advantage for becoming "ecological hubs" of the crypto industry. A critical possibility is the transformation of the geographical distribution: instead of the current concentration in regions with cheap carbon-intensive energy, mining can migrate to regions with an excess of RES with the right economic incentives. Quantification suggests a potential 60-70% reduction of carbon emissions if such directional migration is successfully realized. The third conclusion addresses the limitations of regulatory instruments without technological transformation. The results show that even strict regulatory approaches are only moderately effective: EU information mechanisms were marked for their "high long-term efficiency" but showed only a moderate direct impact on reducing emissions. Regulation can alter economic incentives, but physically reducing carbon emission intensity requires technological solutions. The established effect of carbon leakage under prohibitive regulation is consistent with recent studies demonstrating the migration of activities to countries with lower levels of renewable energy use (Carreras, 2024; Ibañez et al., 2024). However, the magnitude of the effect (a ~ 20% increase in global emissions) identified in our study through expert assessments exceeded existing prognostic estimates. Our study expands this knowledge by identifying a systematic pattern: mining migrates predominantly to regions with cheap but carbon-intensive energy (Kazakhstan, carbon-intensive USA regions) rather than being evenly distributed. These conclusions explain why the empirically observed effect surpasses theoretical predictions: the economic logic of minimizing costs directs migration to the least environmentally friendly locations.
Results regarding the superiority of fiscal instruments over prohibitive approaches are consistent with economic studies proposing corrective taxation to include environmental costs in energy costs (Hebous and Vernon, 2023) and calculations indicating that a tax of $0.047 per kWh could generate an annual revenue of $5.2 billion while lowering emissions by 100 million tons (Siddik et al., 2021). However, our study also demonstrates that the practical implementation of fiscal instruments is complicated by national barriers (industry lobbying) and capital migration risks in the absence of international coordination. The interpretation of the findings points to the need to radically reimagine the strategy of environmental regulation of the crypto industry to achieve real change in reducing environmental damage. The traditional logic of tightening up national requirements should be replaced by the logic of managing global migration towards low-carbon energy systems. The first practical aspect is the reorientation from prohibitive to transformational approaches. The results demonstrate the counterproductiveness of isolated prohibitions. An alternative strategy – a phased transformation through three successive levels (mandatory reporting → economic incentives with differentiated taxation → progressive standards) – allows maintaining regulatory control, directing the industry towards environmental sustainability. The second practical conclusion concerns the role of jurisdictions with abundant RES resources as potential environmental hubs. The identification of natural conditions for RES as a critical factor suggests underutilized potential: regions with excess hydro, geothermal, wind, and solar energy can become centers of concentration of green mining with an active regulatory policy to attract it (Kuandykova et al., 2024; Tashnichenko and Tregub, 2024). The strategy of simultaneously applying incentives in RES regions and fiscal pressure in carbon-intensive regions could steer industry migration in an environmentally preferable direction. The third aspect highlights the unequivocal need for international coordination. Effective regulation requires a minimum of three components: harmonized reporting standards, coordinated fiscal instruments with agreed base rates, and mechanisms of mutual responsibility for the cross-border consequences of regulatory decisions. The fourth and final aspect concerns the need to combine regulatory mechanisms with technological ones. Regulation creates economic incentives, while technology provides an opportunity to physically reduce the impact.

Limitations. The focus of the study on regulatory tools left a detailed analysis of technological alternatives to reduce environmental impact beyond its scope. The full life cycle of environmental impacts, including equipment manufacturing and electronic waste, also fell outside the scope of the research.

CONCLUSIONS

- The findings demonstrate that the effectiveness of regulatory approaches to improving the environmental sustainability of the crypto industry varies significantly depending on the employed tools, institutional contexts, and the degree of international coordination. Nevertheless, information and fiscal mechanisms demonstrate the greatest potential while minimizing unintended negative environmental consequences. Isolated national measures, even strict ones, not only fail to reduce global emissions but can increase them through the mechanism of carbon leakage. Effective reduction of the environmental burden requires the synergy of three components: regulatory pressure, which creates economic incentives for the transition to renewable energy; technological transformation that provides the physical ability to radically reduce energy consumption; and international coordination that prevents the problem from migrating between jurisdictions and thus persisting.
- Instead of the traditional approach through prohibitions and restrictions, which leads high-carbon operations to migrate to regions with less stringent standards, a strategy of directed transformation is proposed. This strategy consists in the phased creation of economic conditions under which environmentally responsible behavior will become more important than it is today. The identification of jurisdictions with an excess of renewable energy as potential centers of concentration of green cryptomining creates an opportunity to not fight the industry but transform it into a tool to dispose of surplus RES. For regulators and policymakers, the findings offer a concrete roadmap for integrating environmental standards with clear timeframes and expected impact scales to reduce the global carbon footprint.
- The scientific contribution of the study is the identified fundamental limitation of national regulation in addressing the global environmental challenges of cross-border digital industries. The discovered contradiction between the local rationality of regulatory choices and global environmental consequences expands the understanding of environmental regulation mechanisms in the context of climate crisis.

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