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CARBON EMISSIONS FROM THE HEALTH-CARE SYSTEM AND BITCOIN MINING IN KAZAKHSTAN: COMPARATIVE TRENDS AND PROJECTIONS, 2016–2030

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Abstract

Introduction. Decarbonization is important for public health, because CO_2 emissions and air pollutants, including $PM_{2.5}$, are associated with increased cardiovascular and respiratory morbidity and premature mortality.

Aim. To compare the dynamics of CO_2 emissions from the health-care system and Bitcoin mining in Kazakhstan and to assess trajectories through 2030 under different scenarios.

Materials and methods. A retrospective ecological time-series analysis covered 2016–2022 and included deterministic scenarios through 2030. National fossil CO_2 and energy indicators were obtained from official statistics (Form 1-TEB). Health-care emissions were estimated top-down as 3.65% of national fossil CO_2, calibrated using the Kazakhstan Health Sector Emissions Fact Sheet. Mining emissions were calculated from annual electricity consumption and the power-system emission factors.

Results. National fossil CO_2 increased from 211.5 to 245.9 Mt. Health-care emissions rose from 7.71 to 8.96 Mt CO_2e at a share of 3.64–3.65%. The trend was significant: β=+0.158 Mt/year, $p=0.031$, $R^2=0.64$. Bitcoin-mining emissions increased from 0.82 to 7.50 Mt CO_2e: β=+1.187 Mt/year, $p<0.001$, $R^2=0.96$. Mining electricity consumption grew from 1,234 to 11,234 GWh, and its share in national electricity use increased from 1.66 to 10.13%. The mining/health ratio increased from 10.7 to 83.7%: β=+0.133/year, $p<0.001$, $R^2=0.97$. In 2021, the health-care emissions structure comprised Scope 1 67% (5.76 Mt), Scope 2 5% (0.43 Mt), and Scope 3 28% (2.40 Mt). Heating and fuel combustion accounted for 57% of the total. The resulting structure indicates that the main mitigation potential in health care is related to building energy retrofits, a transition to clean heat, and improved efficiency of on-site equipment in care delivery settings. Through 2030 under BAU, health care reaches 9.5 Mt and mining 10.4 Mt. Under Health-only, health care decreases to 5.2 Mt, while mining remains 10.4 Mt. Under Joint action, 5.2 Mt for health care and 3.5 Mt for mining are achieved.

Conclusion. Moderate growth in health-care emissions is accompanied by rapid growth in Bitcoin-mining emissions, which by 2022 nearly matched the sector's carbon footprint. The maximum effect is achievable by reducing health-care emissions, primarily Scope 1, and by decarbonizing or restricting mining.

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Key words: Kazakhstan, health care sector, carbon footprint, carbon dioxide, particulate matter, forecasting.

Introduction. Climate change and ambient air pollution are regarded as among the key global threats to public health in the 21st century [1, 2]. According to the World Health Organization, exposure to air pollutants—primarily fine particulate matter ($PM_{2.5}$) – is associated with increased cardiovascular and respiratory morbidity, premature mortality, and substantial losses in life expectancy [3, 4]. In this context, growing attention is being paid not only to traditional emission sources, but also to sectors of the economy that were previously not considered significant determinants of climate-related health risks [5].

The healthcare system occupies a special position in this context [6]. On the one hand, it is intended to reduce the burden of diseases associated with environmental exposures; on the other hand, it itself generates a noticeable carbon footprint due to energy consumption, building heating, medical equipment, pharmaceutical production, and logistics supply chains [7, 8]. International estimates suggest that the healthcare sector accounts for 2% to 5% of global greenhouse gas emissions, while the structure and sources of emissions vary substantially across countries depending on the energy mix and the organization of healthcare delivery [9].

In parallel, recent years have seen rapid growth of energy-intensive digital industries, including cryptocurrency mining based on the proof-of-work mechanism [10]. The high electricity consumption of mining farms and their reliance on carbon-intensive power generation make this sector a potentially significant source of CO_2 emissions and air pollutants [11]. In a number of countries, the contribution of cryptocurrency mining to national electricity consumption and emissions is already comparable to that of traditional industrial sectors, which has raised increasing concern among regulators and experts in environmental protection and public health [12].

The Republic of Kazakhstan represents an illustrative example of a country where these processes are unfolding simultaneously. Kazakhstan’s energy system is characterized by a high share of fossil fuels, primarily coal and gas, which results in high carbon intensity of electricity generation [13]. Against this background, Kazakhstan has in recent years become one of the major centers of cryptocurrency mining, which has been accompanied by a sharp increase in electricity consumption by this sector [14]. At the same time, the country’s healthcare system operates within an energy-intensive infrastructure, including a substantial stock of inpatient facilities with autonomous heat supply and limited electrification of certain processes [15].

Despite the availability of some estimates of the healthcare system’s carbon footprint and a growing number of publications addressing the environmental aspects of cryptocurrency mining, comparative studies that consider healthcare and mining within a single analytical framework remain extremely limited, especially in countries with economies in transition [16]. Existing studies generally lack comparisons of emissions dynamics in these sectors, their relative contributions to national CO_2 emissions, and the potential consequences for public health [17].

In this regard, it is important to conduct a comprehensive analysis in order, based on official statistics, to assess the dynamics of CO_2 emissions from healthcare and bitcoin mining in Kazakhstan, compare their contributions and growth rates, identify key sources of emissions within healthcare, project scenarios through 2030, and provide an approximate estimate of the associated burden on population health.

Thus, the aim of this study is a comparative analysis of the dynamics and projected trajectories of CO_2 emissions from the healthcare system and bitcoin mining in the Republic of

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Kazakhstan in 2016–2030, with an emphasis on their relevance for public health policy and sustainable development.

Materials and Methods.

Ethical issues

The study used aggregated data from open and official sources. Personal data and information enabling identification of individuals were not used; therefore, ethics committee approval was not required.

Study design

The study was conducted as a retrospective ecological time-series analysis aimed at assessing the dynamics and comparative trends of carbon dioxide (CO_2) emissions from the healthcare system and Bitcoin mining in the Republic of Kazakhstan.

The analysis covered the period 2016–2022; in addition, scenario estimates were produced up to 2030. The unit of analysis was the national level; no individual-level data were used.

The study was conducted in accordance with the STROBE recommendations for reporting observational studies, taking into account the specifics of ecological and policy-oriented analyses [18].

Data sources

Data on electricity consumption and the structure of the energy balance of the Republic of Kazakhstan were obtained from official sources of the Bureau of National Statistics of the Agency for Strategic Planning and Reforms of the Republic of Kazakhstan, which is the authorized state body responsible for compiling energy statistics.

Indicators were constructed in accordance with the "Methodology for compiling the fuel and energy balance and calculating selected statistical indicators characterizing the energy sector," approved by Order No. 160 of the Chairman of the Statistics Committee of the Ministry of National Economy of the Republic of Kazakhstan dated August 11, 2016. Data collection is carried out through national statistical observations using Form 1-FEB (annual).

National CO_2 emissions from fossil fuel combustion were used in alignment with international approaches to accounting for energy-related emissions.

Baseline data on healthcare system emissions were obtained from the Kazakhstan Health Sector Emissions Fact Sheet (Health Care Without Harm / Arup), in which total sectoral emissions in 2015 were estimated at 7.34 Mt CO_2-equivalent, corresponding to 2.2% of the national climate footprint and 0.41 t CO_2-equivalent per capita.

To estimate healthcare system emissions in 2016–2022, a proportional approach was applied. A ratio coefficient of healthcare emissions to national CO_2 emissions from fossil fuel combustion in 2015 was calculated. It was assumed that the sector's share of national emissions remained relatively stable over the analyzed period.

Annual healthcare system emissions were calculated by multiplying national CO_2 emissions by this coefficient.

For the structural analysis of healthcare emissions in 2021, a modeled decomposition by Scope 1, Scope 2, and Scope 3 was used, based on national and international estimates of the carbon footprint of the healthcare sector.

Electricity consumption by Bitcoin mining

Electricity consumption volumes of Bitcoin mining farms in Kazakhstan were estimated:

– using a combined approach that included:

– data provided by mining farm operators;

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– analytical reports and publications by companies operating in the cryptocurrency mining sector;

– previously published scientific studies using Kazakhstan's national statistics.

Based on these sources, annual electricity consumption by mining (GWh) and its share in the country's total electricity consumption were determined.

For international comparisons, data from open analytical sources (Visual Capitalist) were used; however, such comparisons were descriptive and were not central to the present study.

Calculation of carbon dioxide emissions

Annual CO_2 emissions from Bitcoin mining were calculated based on electricity consumption volumes using emission factors for Kazakhstan's power system.

Emission factors (kg CO_2-equivalent per kWh) were determined taking into account the electricity generation mix (coal-, gas-, and other power plants) and standard values for the corresponding fuel types.

The average emission factor for the national power system was applied separately for each year and was used to convert electricity consumed by mining into CO_2-equivalent emissions (Mt).

Classification of healthcare system emissions

Healthcare system emissions were classified in accordance with the Greenhouse Gas Protocol (GHG Protocol):

Scope 1 – direct emissions associated with fuel combustion in medical organizations and the operation of on-site generators;

Scope 2 – indirect emissions from consumed electricity and district heat supply;

Scope 3 – indirect emissions related to supply chains (pharmaceutical products, medical equipment), construction, staff and patient transportation, and waste management.

Scenario estimates up to 2030

Scenario modeling of CO_2 emissions up to 2030 was conducted using a deterministic approach with specified end values:

– Business-as-usual (BAU) – continuation of current trends without additional emission-reduction measures.

– Health-only – implementation of decarbonization measures exclusively within the healthcare system.

– Joint action – simultaneous implementation of emission-reduction measures in the healthcare system and the Bitcoin mining sector.

Emission values for 2030 were determined based on expert and literature estimates. Annual trajectories for 2021–2030 were formed by linear interpolation between the baseline values for 2021 and the target values for 2030. Probabilistic or stochastic forecasting models were not applied.

Health burden assessment

For 2021, an illustrative assessment of the health burden associated with emissions from the analyzed sectors was conducted. National estimates of mortality and DALYs attributable to $PM_{2.5}$ exposure were obtained based on Global Burden of Disease–style estimates for Kazakhstan.

Sector-specific mortality and DALYs were calculated by proportionally scaling the national $PM_{2.5}$ burden according to the share of fossil CO_2 emissions attributable to the healthcare system and Bitcoin mining. Uncertainty was expressed as 95% uncertainty intervals (UI) and was inherited from the national estimates.

These calculations were used to compare orders of magnitude and were not intended to establish causal relationships.

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Statistical analysis

Statistical processing was performed using SPSS Statistics version 25. Descriptive statistics were calculated for indicators of electricity consumption and CO_2 emissions. Time-series analysis was applied to assess dynamics over 2016–2022.

Linear regression (OLS) was used to estimate trends in emissions from the healthcare system, Bitcoin mining, and their ratio. Regression results were presented as β coefficients (change per year) with 95% confidence intervals, p-values, and coefficients of determination (R^2). Share analysis was used to assess the contribution of renewable and non-renewable energy sources to mining energy consumption.

Comparative analysis with other Bitcoin-producing countries was descriptive. All statistical tests were two-sided; the level of statistical significance was set at $p < 0.05$.

Results. In 2016–2022, national CO_2 emissions from fossil fuel combustion increased from 211.5 Mt to 245.9 Mt (+16.3% over the period), alongside an increase in estimated healthcare system emissions from 7.71 to 8.96 Mt CO_2 (Table 1).

Table 1. National fossil CO_2 emissions and estimated health-care CO_2 emissions, 2016–2022

Year	Population million	National fossil CO2 Mt	Health Care CO2 Mt	Health Care share national CO2	Bitcoin Mining Electricity GWh	Mining share national electricity
2016	18.4	211.5	7.71	3.65	1234	1.66
2017	18.7	224.3	8.18	3.65	2345	2.92
2018	18.9	226	8.24	3.65	3456	4.03
2019	19.2	214.7	7.83	3.65	4567	5.07
2020	19.5	222.7	8.12	3.65	7234	7.2
2021	19.7	235.2	8.57	3.64	10346	9.79
2022	20	245.9	8.96	3.64	11234	10.13

The linear trend for healthcare emissions was moderate but statistically significant, β = 0.158 Mt per year, 95% CI 0.020–0.295, $p = 0.031$, $R^2 = 0.64$ (Table 3; Figure 1).

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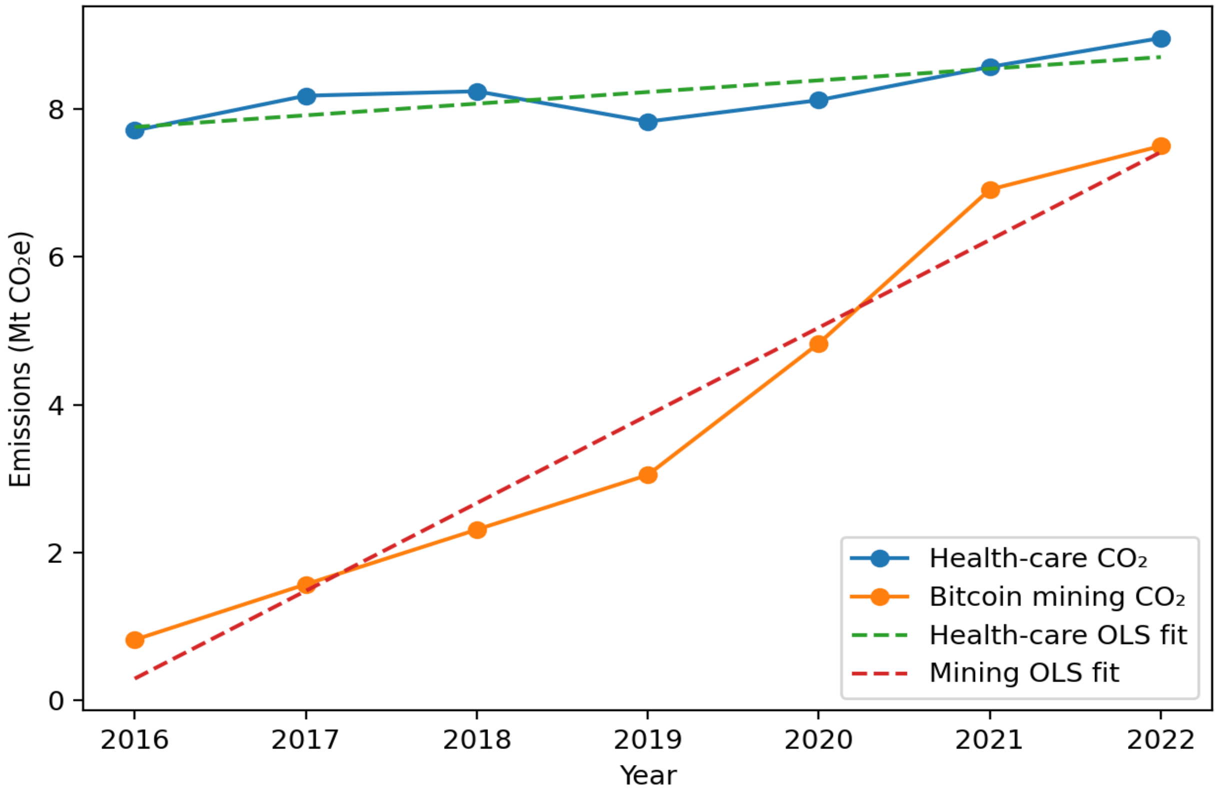

Figure 1. Health-care versus Bitcoin mining CO_2 emissions, 2016–2022

Which in turn corresponds to an average increase of about +1.95% per year relative to the 2016 level, with no signs of acceleration at the end of the series.

For Bitcoin mining over the same period, a sharp rise in estimated emissions was observed from 0.82 to 7.50 Mt CO_2e (Table 2). The linear trend was much more pronounced and highly robust: $\beta = +1.187$ Mt CO_2 per year, 95% CI 0.914–1.460, $p < 0.001$, $R^2 = 0.96$. The share of mining in national fossil CO_2 increased from 0.39% to 3.05%.

Table 2. Healthcare versus Bitcoin mining CO_2 emissions in Kazakhstan, 2016–2022

Year	National fossil CO2 Mt	Health Care CO2 Mt	Bitcoin Mining Electricity GWh	Bitcoin Mining CO2 Mt	Mining share national CO2 pct	Mining CO2 as pct of HealthCare CO2
2016	211.5	7.71	1234	0.82	0.39	10.6
2017	224.3	8.18	2345	1.57	0.7	19.2
2018	226	8.24	3456	2.31	1.02	28
2019	214.7	7.83	4567	3.05	1.42	39
2020	222.7	8.12	7234	4.83	2.17	59.5
2021	235.2	8.57	10346	6.91	2.94	80.6
2022	245.9	8.96	11234	7.5	3.05	83.7

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The convergence of the carbon footprint of mining and healthcare is clearly visible in terms of the mining/health ratio, which increased from 10.7% (2016) to 83.7% (2022) (Figure 2).

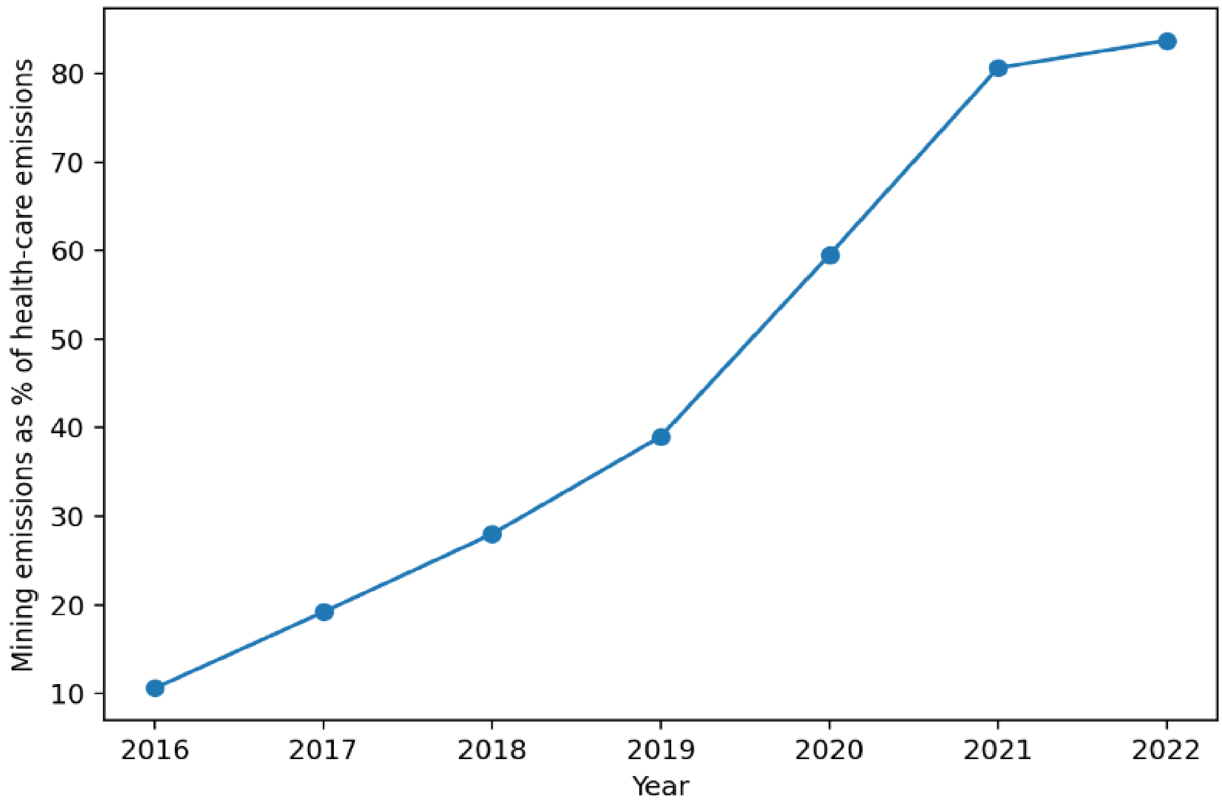

Figure 2. Bitcoin mining emissions as a percentage of health-care emissions

The trend in the ratio was also statistically significant, β = +0.133 per year (i.e., +13.3 percentage points per year in proportion units), 95% CI 0.106–0.161, $p < 0.001$, $R^2 = 0.97$ (Table 3). Practically, this means that across seven points in the series, mining "caught up" with healthcare outliers to about ~0.8 of the sector by 2022.

Table 3. Linear trends in sectoral CO_2 emissions (OLS analysis), 2016–2022

Outcome	**Annual change beta**	**CI 95 % low**	**CI 95 % high**	***p*-value**	**R squared**
Health-care CO_2 emissions (Mt CO_2e)	0.158	0.02	0.295	0.031	0.64
Bitcoin mining CO_2 emissions (Mt CO_2e)	1.187	0.914	1.46	0,001	0.96
Mining-to-health ratio (Mining/Health)	0.133	0.106	0.161	0,001	0.97

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The structure of healthcare system emissions in 2021 was characterized by the dominance of direct sources: Scope 1 = 5.76 Mt CO_2e (67.0%), Scope 2 = 0.43 Mt (5.0%), Scope 3 = 2.40 Mt (28.0%) (Figure 3).

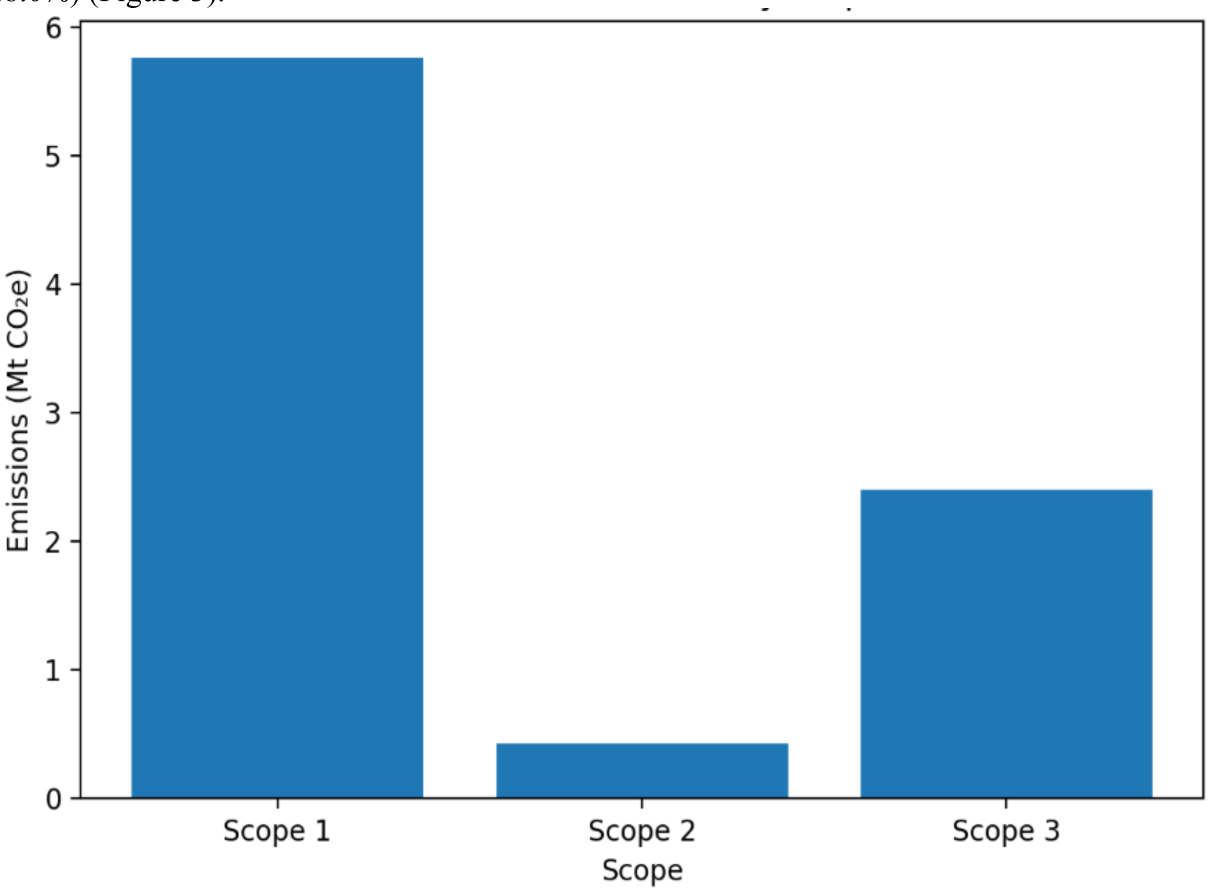

Figure 3. Health-care greenhouse gas emissions by scope, 2021

Within Scope 1, the largest share was attributable to fuel combustion in inpatient facilities and clinics (4.90 Mt; 57.0%), whereas the contribution from generators was 0.86 Mt; 10.0%. The largest components of Scope 3 were associated with pharmaceutical products (0.84 Mt; 9.8%) and medical equipment (0.60 Mt; 7.0%) (Table 4).

Table 4. Breakdown of Kazakhstan's health-care greenhouse gas emissions by scope and sub-sector, 2021

Scope	Category	Emissions Mt CO2e	Share pct
Scope 1	Scope 1 – Fuel combustion in hospitals & clinics	4.9	57
Scope 1	Scope 1 – On-site generators (diesel, gas)	0.86	10
Scope 2	Scope 2 – Grid electricity for facilities	0.34	4
Scope 2	Scope 2 – Purchased district heating / steam	0.09	1
Scope 3	Scope 3 – Pharmaceuticals and chemicals	0.84	9.8
Scope 3	Scope 3 – Medical devices and equipment	0.6	7
Scope 3	Scope 3 – Construction and capital goods	0.36	4.2

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Scope 3	Scope 3 – Staff and patient transport	0.36	4.2
Scope 3	Scope 3 – Waste management and other services	0.24	2.8

Scenario projections to 2030 showed that under a business-as-usual pathway, healthcare emissions increase from 8.6 (2021) to 9.5 Mt CO_2e in 2030 (+0.9 Mt; +10%), while mining emissions increase from 6.9 to 10.4 Mt (+3.5 Mt; +50%) (Table 5; Figure 4).

Table 5. Scenario projections of CO_2 emissions to 2030.

Scenario	**Sector**	**Baseline 2021 MtCO2**	**Projected 2030 MtCO2**	**Absolute change MtCO2**	**Relative change vs 2021**	**Share of projected national 2030**
BAU	Health sector	8.6	9.5	0.9	10	2.6
BAU	Bitcoin mining	6.9	10.4	3.5	50	2.8
Health-only	Health sector	8.6	5.2	-3.4	-40	1.4
Health-only	Bitcoin mining	6.9	10.4	3.5	50	2.8
Joint action	Health sector	8.6	5.2	-3.4	-40	1.4
Joint action	Bitcoin mining	6.9	3.5	-3.5	-50	0.9

In the Health-only scenario, healthcare emissions decrease to 5.2 Mt (−3.4 Mt; −40%); however, mining emissions remain on a growth trajectory up to 10.4 Mt (+50%), meaning the total burden remains high.

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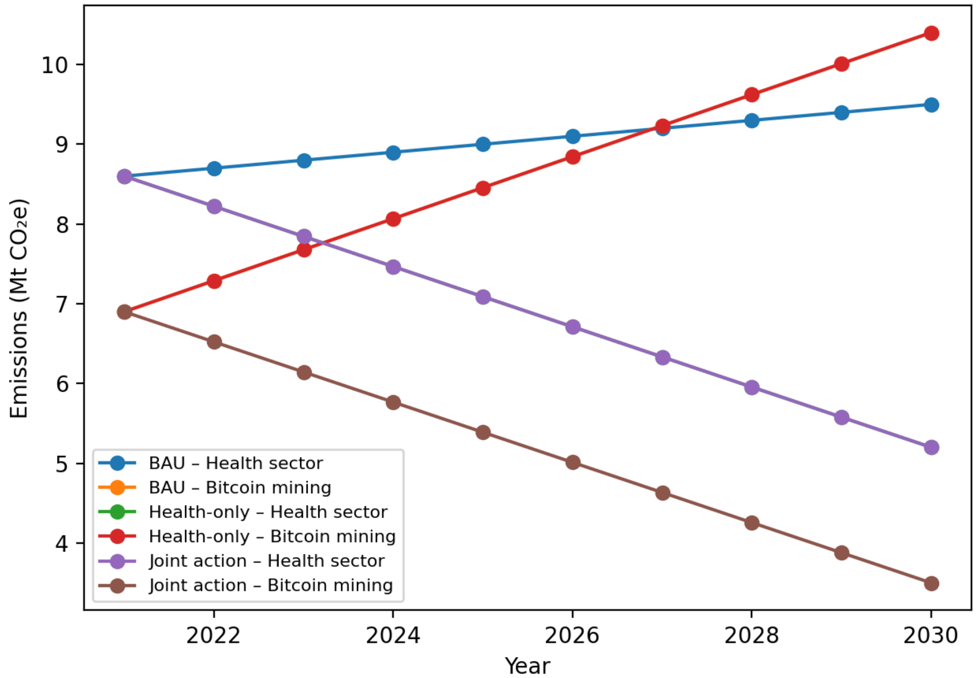

Figure 4. Scenario-based projections of emissions, 2021–2030

Maximum effect is achieved under the Joint action: healthcare decreases to 5.2 Mt (−40%), and mining – to 3.5 Mt (−3.5 Mt; −50%) (Table 5). Here it is important that within the 2021–2030 period the trajectories on the graph are an interpolation between the specified points for 2021 and 2030, rather than an independent year-by-year forecast (Figure 4).

An illustrative estimate of the health burden for 2021 showed comparable orders of magnitude for the healthcare system – 365 deaths per year, 95% UI 255–475, and 8.0 thousand DALYs/year, 95% UI 5.6–10.4; for bitcoin mining – 290 deaths/year, 95% UI 200–380, and 6.5 thousand DALYs/year, 95% UI 4.6–8.4 (Table 6; Figure 5).

Table 6. Estimated health burden attributable to sector-specific emissions, 2021.

Sector	**Share of national fossil CO2**	**PM25 attrib deaths n**	**Deaths 95UI**	**PM25 attrib DALYs thousands**	**DALYs 95UI thousands**	**Main causes ranked**
Health sector	3.6	365	255–475	8	5.6–10.4	Ischaemic heart disease, stroke, COPD, lung cancer
Bitcoin mining	2.9	290	200–380	6.5	4.6–8.4	Ischaemic heart disease, stroke, COPD
Combined	6.5	655	455–855	14.5	10.2–18.8	Cardiovascular and chronic respiratory diseases

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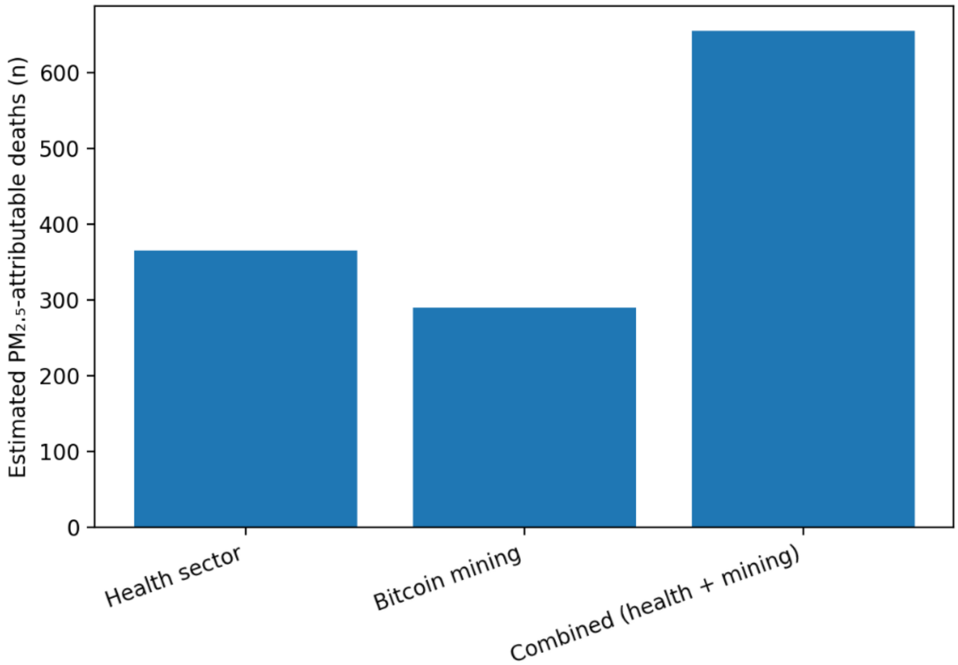

Figure 5. Illustrative $PM_{2.5}$-attributable mortality, 2021

Cumulatively, the two sectors accounted for 655 deaths/year (95% UI 455–855) and 14.5 thousand DALYs/year (95% UI 10.2–18.8) (Table 6).

Discussion. The present study showed that in Kazakhstan in 2016–2022, the rise in national CO_2 emissions from fossil fuel combustion was accompanied by a moderate increase in the estimated carbon footprint of the healthcare system, whereas emissions associated with bitcoin mining grew substantially faster and by the end of the period approached the scale of the entire healthcare sector.

Estimated healthcare system emissions increased from 7.71 to 8.96 Mt CO_2e against the background of rising national fossil CO_2 from 211.5 to 245.9 Mt. At the same time, the linear trend in healthcare emissions remained moderate ($\beta = +0.158$ Mt/year, 95% CI 0.020–0.295, $p = 0.031$, $R^2 = 0.64$). Such dynamics appear expected for a sector whose infrastructure is inertial: capital assets (inpatient facilities, heating systems, boiler houses, engineering networks) change slowly; therefore, annual increments are typically close to linear and reflect overall growth in energy consumption and system load [9].

Bitcoin mining showed a completely different pattern: emissions grew from 0.82 to 7.50 Mt CO_2e, and the trend was almost “perfectly” linear for a short series of observations ($\beta = +1.187$ Mt/year, 95% CI 0.914–1.460, $p < 0.001$, $R^2 = 0.96$). In practical terms, this means that the annual additional climate impact of mining was an order of magnitude higher than that of healthcare and, within the observed period, remained stable [11]. A likely explanation is rapid changes in the industry’s scale (expansion of farm capacity) under relatively stable carbon intensity of the power system [19].

Particularly illustrative is the convergence of the sectors in terms of the mining/health ratio: an increase from 10.7% to 83.7% over 2016–2022 and a statistically significant trend ($\beta = +0.133$/year, 95% CI 0.106–0.161, $p < 0.001$, $R^2 = 0.97$). This is not merely mining growth; it is

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quantitative evidence that within a few years, a sector unrelated to core social infrastructure approached the entire national healthcare system in climate footprint. For the debate on decarbonization priorities, this is a strong argument that focusing exclusively on "traditional" sectors is insufficient [16].

Structural decomposition of healthcare emissions for 2021 shows the dominance of Scope 1 – 67% (5.76 Mt CO_2e), whereas Scope 2 accounts for 5% and Scope 3 for 28%. Within Scope 1, the main contribution is associated with fuel combustion in medical organizations (4.90 Mt; 57%), while generators contribute 0.86 Mt; 10%. This profile logically aligns with the characteristics of heat supply and energy consumption of inpatient facilities in countries with a high share of coal and gas in the energy mix and a significant role of local heating solutions [20].

The practical implication here is rather straightforward: the fastest and potentially largest effects in healthcare should be expected from measures targeting heat and fuel (building energy efficiency, modernization of boiler houses/heat substations, switching to less carbon-intensive fuels, reducing the need for autonomous generation), rather than only from "electrification" or electricity procurement. Against this background, the relatively small share of Scope 2 (5%) means that even radical changes in consumed electricity will yield limited impact unless the issue of heat and direct fuel combustion is addressed [21].

At the same time, the Scope 3 share (28%) requires cautious interpretation. In the international literature, for many countries healthcare supply chains can dominate [22]. In this case, the estimate is likely conservative, because aggregated assumptions and incomplete detailed data on procurement, logistics, and life cycles of medical products may lead to underestimation. This does not invalidate the conclusions, but it sets the direction for the next step: expanding the Scope 3 inventory and moving from modeled shares to more "bottom-up" data (procurement categories, volumes, and suppliers) [23].

Scenario estimates through 2030 reinforce the core meaning of the comparison. Under business-as-usual, healthcare emissions increase to 9.5 Mt CO_2e (+10% relative to 2021), whereas mining emissions reach 10.4 Mt (+50%). That is, if trajectories are maintained, mining is capable not only of "catching up with" but also surpassing the healthcare sector in carbon footprint [11, 19].

The Health-only scenario demonstrates an important governance paradox: even if healthcare reduces emissions to 5.2 Mt (−40%), mining growth to 10.4 Mt will maintain a high overall burden. This underscores the need for an intersectoral approach. The most pronounced effect is achieved only under Joint action (healthcare 5.2 Mt, mining 3.5 Mt), that is, with simultaneous implementation of measures in both sectors. In essence, the results propose a policy framework: decarbonization of healthcare should proceed in parallel with regulation of the energy profile of energy-intensive digital industries; otherwise, part of the effect will be offset at the level of national emissions [24].

Importantly, the annual trajectories for 2021–2030 in the study were constructed as interpolation between specified points rather than as a time-series forecast. This limits interpretation in terms of "precise year-by-year prediction" but it does not reduce the value of the scenario comparison: it shows the order of magnitude of potential changes and the differences between strategies [25].

An illustrative estimate of the health burden for 2021 showed comparable orders of magnitude: for healthcare – 365 deaths/year (95% UI 255–475) and 8.0 thousand DALYs (95% UI 5.6–10.4); for mining – 290 deaths/year (95% UI 200–380) and 6.5 thousand DALYs (95% UI

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4.6–8.4); in total – 655 deaths (95% UI 455–855) and 14.5 thousand DALYs (95% UI 10.2–18.8). These values are important as a communication bridge between “tons of CO_2” and outcomes that are understandable for the healthcare system [26].

At the same time, the method of scaling the burden by the share of fossil CO_2 is a simplifying one. It is useful for estimating orders of magnitude and comparing sectors, but it does not replace full-fledged models linking source emissions to $PM_{2.5}$ concentrations and subsequent risks (e.g., through emissions inventories, atmospheric modeling, and concentration–response functions) [27]. This assumption requires further validation, especially in the regional context of Kazakhstan, where the contribution of different sources to $PM_{2.5}$ may vary substantially across regions and seasons.

Study limitations

This study has several limitations. The first limitation is related to the assessment of healthcare emissions based on a fixed share of national fossil CO_2 (a coefficient of 3.65%). The second limitation is the uncertainty in estimating the energy consumption of mining. Although a combined approach was used, the industry is characterized by high volatility, regulatory changes, and possible incompleteness of reporting. Nevertheless, the high explained variance of the trend ($R^2 = 0.96$) and narrow confidence intervals for β indicate the robustness of the overall dynamics within the selected period. The third limitation is that scenario modeling up to 2030 is deterministic in nature and is intended for comparing strategies rather than for accurate forecasting.

Conclusion. In 2016–2022, CO_2 emissions from Kazakhstan’s healthcare system grew moderately and linearly, whereas emissions associated with bitcoin mining increased much faster and by 2022 became comparable in scale to emissions from the entire healthcare sector. The main contribution to healthcare’s carbon footprint comes from direct emissions (Scope 1), primarily heating and local fuel combustion, which makes decarbonizing the thermal infrastructure of medical organizations a priority. The rapid growth of energy-intensive digital industries, including cryptocurrency mining, can offset the effects of healthcare decarbonization in the absence of cross-sector regulation. Scenario estimates through 2030 show that a substantial reduction in total emissions is possible only if measures are implemented simultaneously in the healthcare system and in the bitcoin-mining sector. Illustrative estimates of the health burden indicate comparable orders of impact from healthcare and bitcoin-mining emissions, underscoring the importance of climate policy for public health.

Conflict of interest. The authors declare no conflict of interest.

Authors' contribution. Concept, AK and MY; methodology, AK; writing- preparation of the manuscript, AK, MY, AK, OV; writing - draft and editing, AK, MY, AK, OV; project administration, AK; All authors have read and agreed to the published version of the manuscript. The authors declare that this material has not been previously published and is not under consideration by other publishers.

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ҚАЗАҚСТАНДАҒЫ ДЕНСАУЛЫҚ САҚТАУ ЖҮЙЕСІ МЕН БИТКОИН МАЙНИНГІНЕН ТУЫНДАЙТЫН КӨМІРТЕК ШЫҒАРЫНДЫЛАРЫ: 2016–2030 ЖЫЛДАР АРАЛЫҒЫНДАҒЫ САЛЫСТЫРМАЛЫ ҮРДІСТЕР МЕН БОЛЖАМДАР

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Түйіндеме

Кіріспе. Декарбонизация қоғамдық денсаулық үшін маңызды, өйткені CO_2 шығарындылары және ауа ластағыштары, соның ішінде $PM_{2.5}$, жүрек-қантамыр және респираторлық аурушаңдықтың артуымен және мерзімінен бұрын өлім-жітіммен байланысты.

Мақсаты. Қазақстандағы денсаулық сақтау жүйесі мен биткоин-майнингтің CO_2 шығарындыларының динамикасын салыстыру және әртүрлі сценарийлер жағдайында 2030 жылға дейінгі траекторияларды бағалау.

Материалдар мен әдістер. Ретроспективті экологиялық уақыттық талдау 2016–2022 жылдарды қамтып, 2030 жылға дейін детерминистік сценарийлерді енгізді. National fossil CO_2 және энергетикалық көрсеткіштер ресми статистикадан (1-ТЭБ) алынды. Денсаулық сақтау шығарындылары top-down тәсілімен national fossil CO_2-тың 3,65% үлесі ретінде бағаланып, Kazakhstan Health Sector Emissions Fact Sheet бойынша калибрленді. Майнинг шығарындылары жылдық энергия тұтынуы және электр энергетикалық жүйенің шығарындылар коэффициенттері бойынша есептелді.

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Нәтижелер. National fossil CO_2 211,5-тен 245,9 Mt-қа дейін өсті. Денсаулық сақтау шығарындылары 3,64–3,65% үлес жағдайында 7,71-ден 8,96 Mt CO_{22}e-ке дейін ұлғайды. Тренд мәнді болды: β=+0,158 Mt/жыл, $p=0{,}031$, $R^2=0{,}64$. Биткоин-майнинг шығарындылары 0,82-ден 7,50 Mt CO_2e-ке дейін өсті: β=+1,187 Mt/жыл, $p<0{,}001$, $R^2=0{,}96$. Майнингтің энергия тұтынуы 1234-тен 11234 ГВт·сағ-қа дейін артты, ал елдің электр тұтынуындағы үлесі 1,66-дан 10,13%-ға дейін көбейді. mining/health қатынасы 10,7-ден 83,7%-ға дейін өсті: β=+0,133/жыл, $p<0{,}001$, $R^2=0{,}97$. 2021 жылы денсаулық сақтау шығарындыларының құрылымы Scope 1 67% (5,76 Mt), Scope 2 5% (0,43 Mt) және Scope 3 28% (2,40 Mt) болды. Жылыту және отынды жағу жалпы көлемнің 57%-ын қамтамасыз етті. Алынған құрылым денсаулық сақтаудағы негізгі төмендету резерві ғимараттарды энергия тиімді жаңғыртумен, таза жылуға көшумен және медициналық көмекті көрсету орындарында жабдықтың тиімділігін арттырумен байланысты екенін көрсетеді. 2030 жылға дейін BAU сценарийінде денсаулық сақтау 9,5 Mt-қа, майнинг 10,4 Mt-қа жетеді. Health-only сценарийінде денсаулық сақтау 5,2 Mt-қа дейін төмендейді, майнинг 10,4 Mt деңгейінде қалады. Joint action сценарийінде денсаулық сақтау үшін 5,2 Mt және майнинг үшін 3,5 Mt көрсеткіштеріне қол жеткізіледі.

Қорытынды. Денсаулық сақтау шығарындыларының қалыпты өсуі биткоин-майнинг шығарындыларының жылдам өсуімен қатар жүреді, ал 2022 жылға қарай майнинг сектордың көміртек ізімен дерлік теңесті. Ең жоғары әсер денсаулық сақтау шығарындыларын, ең алдымен Scope 1 бойынша, қысқарту және майнингті декарбонизациялау немесе шектеу жағдайында мүмкін.

Түйінді сөздер: Қазақстан, денсаулық сақтау секторы, көміртек ізі, көмірқышқыл газы, қатты бөлшектер, болжау.

ВЫБРОСЫ УГЛЕРОДА ОТ СИСТЕМЫ ЗДРАВООХРАНЕНИЯ И МАЙНИНГА БИТКОИНА В КАЗАХСТАНЕ: СРАВНИТЕЛЬНЫЕ ТРЕНДЫ И ПРОГНОЗЫ, 2016–2030 гг.

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Аннотация

Введение. Декарбонизация важна для общественного здравоохранения, поскольку выбросы CO_2 и загрязнители воздуха, включая $PM_{2.5}$, связаны с ростом сердечно-сосудистой и респираторной заболеваемости и преждевременной смертности.

Цель. Сопоставить динамику выбросов CO_2 системы здравоохранения и биткоин-майнинга в Казахстане и оценить траектории до 2030 года при разных сценариях.

Материалы и методы. Ретроспективный экологический временной анализ охватил 2016–2022 годы и включал детерминированные сценарии до 2030 года. National fossil CO_2 и энергетические показатели получены из официальной статистики (1-ТЭБ). Выбросы

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здравоохранения оценивали top-down как долю 3,65% от national fossil CO_2, калиброванную по Kazakhstan Health Sector Emissions Fact Sheet. Выбросы майнинга рассчитывали по годовому энергопотреблению и коэффициентам выбросов энергосистемы.

Результаты. National fossil CO_2 выросли с 211,5 до 245,9 Mt. Выбросы здравоохранения увеличились с 7,71 до 8,96 Mt CO_2e при доле 3,64–3,65%. Тренд был значимым: β=+0,158 Mt/год, p=0,031, R^2=0,64. Выбросы биткоин-майнинга выросли с 0,82 до 7,50 Mt CO_2e: β=+1,187 Mt/год, p<0,001, R^2=0,96. Энергопотребление майнинга увеличилось с 1234 до 11234 ГВт·ч, а доля в электропотреблении страны – с 1,66 до 10,13%. Отношение mining/health выросло с 10,7 до 83,7%: β=+0,133/год, p<0,001, R^2=0,97. В 2021 году структура выбросов здравоохранения включала Scope 1 67% (5,76 Mt), Scope 2 5% (0,43 Mt) и Scope 3 28% (2,40 Mt). Отопление и сжигание топлива обеспечивали 57% общего объема. Полученная структура указывает, что ключевой резерв снижения в здравоохранении связан с энергомодернизацией зданий, переходом на чистое тепло и повышением эффективности оборудования на местах оказания помощи. До 2030 года при BAU здравоохранение достигает 9,5 Mt, майнинг 10,4 Mt. При Health-only здравоохранение снижается до 5,2 Mt, майнинг остается 10,4 Mt. При Joint action достигаются 5,2 Mt для здравоохранения и 3,5 Mt для майнинга.

Заключение. Умеренный рост выбросов здравоохранения сопровождается быстрым ростом выбросов биткоин-майнинга, который к 2022 году почти сравнялся с углеродным следом сектора. Максимальный эффект возможен при снижении выбросов здравоохранения, прежде всего Scope 1, и при декарбонизации или ограничении майнинга.

Ключевые слова: Казахстан, сектор здравоохранения, углеродный след, диоксид углерода, твердые частицы, прогнозирование.