

# SUSTAINABLE BLOCKCHAIN MODELS: A COMPARATIVE LIFE CYCLE ASSESSMENT OF PROOF OF WORK AND PROOF OF SPACE AND TIME

*MODELOS DE BLOCKCHAIN SUSTENTÁVEIS:  
UMA AVALIAÇÃO COMPARATIVA DO CICLO DE VIDA DE  
PROVA DE TRABALHO E PROVA DE ESPAÇO E TEMPO*

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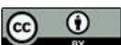
## Abstract

The study investigates the environmental, economic, and educational dimensions of blockchain consensus mechanisms, focusing on a comparative analysis between Proof of Work (PoW) and Proof of Space and Time (PoST). Using an experimental mixed-methods approach, the research combines empirical energy consumption measurements, life cycle assessment (LCA), and economic modeling to evaluate sustainability performance. Results demonstrate that PoST reduces energy consumption by approximately 90–95% and decreases CO<sub>2</sub> emissions by up to 93% compared to PoW, while maintaining network decentralization and security. Although PoST shifts part of the ecological burden from operational energy use to hardware production and disposal, its overall life cycle impact remains significantly lower. The findings confirm PoST's potential as a viable alternative for sustainable blockchain development and align with the principles of the EU Green Deal and ESG frameworks. Furthermore, the study highlights the didactic value of cryptocurrency farming for interdisciplinary education in informatics, economics, and environmental sciences, emphasizing the role of universities in fostering responsible technological innovation.

**Keyword:** Proof of Work. Proof of Space and Time. Blockchain Sustainability.

## Resumo

O estudo investiga as dimensões ambientais, econômicas e educacionais dos mecanismos de consenso em blockchain, com foco em uma análise comparativa entre Prova de Trabalho (PoW) e Prova de Espaço e Tempo (PoST). Utilizando uma abordagem experimental de métodos mistos, a pesquisa combina medições empíricas de consumo de energia, avaliação do ciclo de vida (ACV) e modelagem econômica para avaliar o desempenho em sustentabilidade. Os resultados demonstram que o PoST reduz o consumo de energia em aproximadamente 90–95% e diminui as emissões de CO<sub>2</sub> em até 93% em comparação com o PoW, mantendo a descentralização e a segurança da rede. Embora o PoST transfira parte do ônus ecológico do uso de energia operacional para a produção e descarte de hardware, seu impacto geral no ciclo de vida permanece significativamente menor. As descobertas confirmam o potencial do PoST como uma alternativa viável para o desenvolvimento sustentável de blockchain e estão alinhadas aos princípios do Pacto Ecológico Europeu e às estruturas ESG. Além disso, o estudo destaca o valor didático do farming de criptomoedas para a educação interdisciplinar em informática, economia e ciências ambientais, enfatizando o papel das universidades no fomento da inovação tecnológica responsável.



Cryptocurrency Informatics. Farming. Environmental

**Palavras-chave:** *Prova de Trabalho. Prova de Espaço e Tempo. Sustentabilidade da Blockchain. Cultivo de Criptomoedas. Informática Ambiental.*

## 1 INTRODUCTION

The technological concept of blockchain represents a revolution in the field of secure data storage and sharing without the need for a central authority [1]. Each block contains a set of transactions and a cryptographic hash of the previous block, forming a chronologically linked chain that ensures data immutability and transparency.

The primary advantage of blockchain lies in establishing trust through mathematical consensus rather than institutional authority. However, this principle entails high energy costs, as block validation across the network requires substantial computational power distributed among thousands of devices worldwide [2][3].

In recent years, research has increasingly focused on assessing the sustainability of decentralized technologies. According to de Vries [5], Bitcoin alone can generate more CO<sub>2</sub> emissions than entire countries such as Qatar or the Czech Republic. In response, various initiatives have emerged to reduce blockchain's energy intensity through alternative consensus mechanisms emphasizing efficiency, renewable energy sources, and hardware recycling [4][5][6].

## 2 THEORETICAL BACKGROUND

### 2.1 Proof of work and its limitations

The *Proof of Work (PoW)* mechanism is historically the first and still the most widely used method of transaction verification. *Proof of Work (PoW)*, first implemented by *Satoshi Nakamoto* in the *Bitcoin* system [2], remains the most prevalent consensus algorithm within the cryptocurrency ecosystem.

The system's security is ensured by requiring users (*miners*) to compete in solving computationally demanding cryptographic puzzles. Although this principle provides high resistance to attacks, it is extraordinarily energy-intensive [7].

Its core concept lies in solving complex mathematical problems (so-called *hash puzzles*), the goal of which is to find a number that, when processed through a hashing function, meets a predefined difficulty condition.

This process, known as *mining*, represents competition among network nodes for the right to create a new block and receive a reward in the form of newly issued coins and transaction fees.

From a security perspective, PoW is highly robust – an attack on the network would require control of more than 50 % of the total computational power (*hashrate*), which is economically and technically extremely expensive.

At the same time, however, this very feature constitutes, as mentioned above, its major weakness – enormous energy consumption.

According to *Stoll et al.* [7], the energy efficiency of PoW is physically limited – greater security always requires higher computational power. The *Cambridge Bitcoin Electricity Consumption Index (CBECEI)* [1] reported that in 2024, Bitcoin's annual energy consumption reached **127 TWh**, which is comparable to the total electricity use of the Netherlands. This energy demand generates approximately **65–70 million tons of CO<sub>2</sub>** per year, which, according to *Stoll et al.* [6], corresponds to the carbon footprint of a medium-sized European country.

Research by the *International Energy Agency (IEA)* [8] further indicates that cryptocurrency mining already accounts for **0.35 % of global electricity consumption**.

### 2.1.1 Economic and environmental inefficiency

The fundamental principle of *Proof of Work (PoW)* lies in computational competition – the more devices a miner owns, the higher the probability of successfully mining a block. As a result, the network's total computational power grows exponentially, driven not by technological necessity but by economic motivation.

The total *Bitcoin* network hashrate increased from **40 EH/s in 2018** to more than **600 EH/s in 2024** [4].

However, the actual *useful work* – verifying transactions – represents less than **0.0001 %** of all computations, while the remaining energy is wasted on generating random hashes that are immediately discarded.

This phenomenon is often referred to as the *proof-of-waste paradox* [10]: the more secure the network becomes, the greater its environmental burden. From a game theory perspective, this represents a classic case of the *tragedy of the commons*, where individual optimization (higher computing power = higher profit) leads to collective inefficiency.

The energy intensity of PoW is also highly uneven geographically, creating a so-called *race to the bottom* – miners relocate to regions with the cheapest electricity, often derived from fossil fuels. This has significant environmental and social implications. Mining farms tend to concentrate in areas with inexpensive energy (e.g., Sichuan Province, Kazakhstan, Texas), frequently relying on non-renewable sources [3][8].

After the mining ban in China (2021), more than **40 % of global Bitcoin mining** relocated to the United States, where the energy mix remains largely dependent on coal and natural gas [11].

### 2.1.2 Social and material impacts

*Proof of Work (PoW)* also generates social inequalities between large and small miners. As computational difficulty increases and the need for specialized hardware (*ASICs*) grows, mining power becomes increasingly concentrated in the hands of a few corporations.

According to data from 2024, the five largest mining pools controlled more than **70 %** of Bitcoin's total computational capacity [12]. This has led to a *de facto* centralization of a system originally designed to be decentralized.

In addition to the energy burden, it is necessary to consider the *material footprint* of PoW.

According to the *World Bank* (2023) [13] and the *Global E-waste Monitor* (2024), approximately **25–30 thousand tons** of electronic waste are generated annually from discarded mining equipment.

The average lifespan of *ASIC miners* ranges between **18 and 24 months**, after which they become economically obsolete. Most components are non-recyclable due to the complex combination of materials and solder alloys, which further increases the ecological impact of cryptocurrency mining.

### 2.1.3 Environmental externalities and regulatory pressure

In response to these challenges, governments and international organizations have begun to consider regulating *Proof of Work (PoW)* mining. For example, *Sweden* and *Norway* proposed in **2023** to ban industrial-scale cryptocurrency mining powered by non-renewable energy sources [14].

Within the framework of the *Markets in Crypto-Assets Regulation (MiCA, 2024)* [12], the *European Commission* introduced mandatory transparency requirements regarding the environmental impact of crypto projects and initiated discussions on including mining activities in the *EU Taxonomy for Sustainable Activities* [15].

Some projects have reacted to the growing pressure by adopting *carbon-compensated mining* models or by utilizing *waste energy* from industrial sources. For instance, *Crusoe Energy Systems* uses flare gas from oil extraction to power mining facilities, thereby reducing methane emissions into the atmosphere. Similar approaches are emerging in *Canada* and the *United States*, where surplus electricity from hydro and wind power plants is redirected to cryptocurrency mining.

### 2.1.4 Summary of PoW limitations

From a theoretical perspective, *Proof of Work (PoW)* provides the highest level of security and decentralization; however, in practice, it represents the least sustainable and most environmentally problematic solution.

Its main limitations can be summarized as follows:

1. **Extreme energy consumption** – approximately **100–130 TWh per year**.
2. **High carbon footprint** – **60–70 Mt CO<sub>2</sub> annually**.
3. **Short hardware lifespan and generation of e-waste** – over **25,000 tons per year**.
4. **Concentration of computational power** – **70 % of total hashrate** controlled by five mining pools.
5. **Low work efficiency** – only a tiny fraction of computations produces meaningful results.

From an economic standpoint, PoW is becoming increasingly unsustainable: as computational difficulty rises, the profitability of small miners declines, leading to the

concentration of mining power in large data centers [10]. This trend undermines the fundamental principle of decentralization upon which cryptocurrencies were originally built. These issues form the core argument for developing alternative approaches such as *Proof of Stake (PoS)*, *Proof of Space and Time (PoST)*, and hybrid models that aim to combine blockchain security with the sustainability of the digital economy [4][5][16].

## 2.2 Proof of Stake, Proof of Space, and Proof of Space and Time

An alternative to *Proof of Work (PoW)* is *Proof of Stake (PoS)*, which replaces computational competition with an economic stake. A further evolutionary step is represented by the extended variant of PoS – *Proof of Space and Time (PoST)*. These models utilize unused disk storage as a source of trust. Instead of computational power, the determining factor is the amount of stored data blocks (*plots*) [17]. Combined with a temporal component (*Proof of Time*), the system verifies that the participant genuinely possesses the allocated space and actively contributes to the network [18].

The *Proof of Space and Time (PoST)* mechanism represents one of the most significant innovations in blockchain consensus algorithms.

Its principle lies in using free disk space as a means of transaction verification, thereby replacing the energy-intensive computational competition typical of *Proof of Work (PoW)* [17][4]. PoST is based on two interrelated concepts – *Proof of Space (PoS)* and *Proof of Time (PoT)*. While the first verifies that the participant possesses a certain amount of storage capacity, the second ensures that this space is utilized consistently and honestly over time.

This model offers a fundamental environmental advantage: instead of continuously computing hashes (as in PoW), it suffices to generate and maintain data blocks (*plots*) that can be reused multiple times. Energy is thus required only during the initial “seeding” (*plotting*) of disk space, not during the ongoing operation of the network.

*Chia Network*, founded by *Bram Cohen*, was the first project to implement this concept in practice. Its algorithm employs cryptographic proofs of both space and time, while its computational requirements are negligible compared to PoW. According to the analysis by *Greenfield and Zhao* [4], the *Chia Network* consumes approximately **0.5 %** of the annual energy used by Bitcoin, while achieving a comparable level of security and decentralization.

### 2.2.1 Technological principle of farming

The farming process consists of two main phases – *plotting* and *farming*. During *plotting*, cryptographically generated data structures are written to HDD or SSD drives, each containing a set of random numerical sequences. These sequences function as “lottery tickets” in the competition for the right to create a new block. In each round, one of these sequences is randomly selected – if it meets the network’s current difficulty requirements, the farmer receives a reward.

This approach results in significantly lower energy consumption, as the operational *farming* phase requires only a few dozen watts of power. From a performance perspective, *Proof of Space and Time (PoST)* is therefore suitable even for home users, enhancing decentralization and reducing the dominance of large corporations. Whereas *PoW* mining farms demand specialized hardware (*ASICs*) and industrial cooling systems, *PoST* relies on standard computer equipment, making it more accessible and environmentally efficient.

### 2.2.2 Environmental aspects of PoST

Although *Proof of Space and Time (PoST)* is highly energy-efficient, it cannot be described as entirely *carbon-neutral*. The primary environmental challenge lies in the burden associated with the production and disposal of storage devices. According to the *World Bank* [13] and the *European Environment Agency (EEA)* [6], the manufacturing of a **1 TB HDD** is associated with approximately **35–40 kg CO<sub>2</sub>eq** emissions, while an SSD has a slightly higher carbon footprint due to the production of NAND flash chips. For smaller farms (up to **100 TB**), however, these emissions account for less than **5 %** of the emissions that would otherwise be generated by operating GPU-based mining under the *PoW* system.

Another environmental factor is the **lifespan of drives**. *PoST* increases SSD wear during the *plotting* phase – the generation of data blocks [19]. This partially shifts the ecological burden from the energy domain to the material domain. Intensive plotting can significantly shorten SSD lifespan; therefore, *enterprise-grade* models with higher write endurance (*DWPD – Drive Writes Per Day*) are now preferred.

From a *circular economy* perspective, these drives can be **recycled or refurbished** after their farming lifecycle, thus closing their material loop [6]. Environmentally, PoST can therefore be classified as a technology with **low operational** but **moderate material intensity**. Nevertheless, according to comprehensive *Life Cycle Assessment (LCA)* evaluations, PoST remains the most efficient known consensus mechanism [5][6].

Despite these factors, its overall environmental impact is still approximately **90–95 % lower** than that of PoW [5].

### 2.2.3 Economic and social impacts

The economic logic of *Proof of Space and Time (PoST)* differs fundamentally from that of *Proof of Work (PoW)*. Instead of massive investments in computational hardware, the key factors are the availability of disk storage and the efficiency of data management.

This opens participation opportunities for ordinary users, educational institutions, and small organizations that can actively contribute to the operation of the blockchain network.

From this perspective, PoST introduces a **social dimension of decentralization** – it lowers entry barriers and promotes a more equitable distribution of rewards across the network [20]. According to *Chen et al.* [5], PoST can be regarded as a *democratized blockchain* model that aligns more closely with the original vision of a decentralized economy.

Moreover, its low operating costs enable viable participation even in regions with high electricity prices, thereby expanding the network's **geographical inclusivity** and supporting a more globally distributed digital infrastructure.

### 2.2.4 PoST and the educational context

The significance of *Proof of Space and Time (PoST)* extends beyond the technological domain, encompassing education and digital literacy.

As *Hubálovský et al.* [21] note, the concept of *farming* can serve as a **didactic tool** in teaching *environmental informatics*. Students can practically measure energy

consumption, monitor device temperature stability, analyze CO<sub>2</sub> emissions, and relate these findings to the principles of sustainable development.

Within the framework of the *European Digital Competence Framework (DigComp 2.2)* [22], PoST aligns with the areas of “*digital citizenship*” and “*sustainable use of technology*.” Integrating these aspects into the educational process fosters **critical thinking about technology** and helps students understand the broader social implications of digitalization.

### 2.2.5 Hybrid models and the path toward a “Green Blockchain”

Rapid technological progress has led to the emergence of hybrid consensus models that combine various mechanisms such as *Proof of Stake (PoS)*, *Proof of Space and Time (PoST)*, and additional elements like *Proof of Authority* or *Proof of Storage and Stake* [18][16]. The goal is to maintain security and decentralization while simultaneously reducing both the energy and material footprint of blockchain operations.

According to the *Cardano Foundation* [23], recent years have seen the rise of *carbon-aware blockchains* that actively optimize their performance based on the availability of renewable energy sources. These systems can dynamically decrease computing power during periods of high electricity demand and increase it when renewable energy is abundant.

The concept of *green mining* is also developing – involving the utilization of waste heat from computational processes for heating residential and office buildings [24][25]. This approach transforms waste heat into a useful byproduct, potentially reducing the real carbon footprint of data centers.

The *European Commission* [26][15] emphasizes that digital transformation must align with the objectives of the *European Green Deal* and *ESG taxonomy*. By **2030**, most new digital services are expected to provide transparent data on energy consumption and emissions. Consequently, cryptocurrency projects face increasing pressure to improve *environmental reporting* and transition toward renewable energy sources [12].

### 2.2.6 Summary of theoretical findings

The current state of research confirms that next-generation consensus mechanisms (*PoS*, *PoST*, and hybrid models\*) represent a crucial step toward *sustainable digitalization*.

While *Proof of Work (PoW)* is inherently environmentally unsustainable, *Proof of Space and Time (PoST)* offers a balanced solution – significantly reducing energy consumption while maintaining sufficient levels of security and decentralization.

The future of blockchain technology will likely evolve toward **intelligent, energy-aware, and materially responsible networks**, whose operation will be managed by artificial intelligence and interconnected with renewable energy sources [6][16].

## 3 RESEARCH OBJECTIVE AND METHODOLOGICAL FRAMEWORK

The objective of this research was to quantitatively and qualitatively assess the differences between two blockchain consensus models – *Proof of Work (PoW)* and *Proof of Space and Time (PoST)* – in terms of **energy consumption, environmental impact, and economic efficiency**.

The study stemmed from the need to demonstrate to university students in the fields of engineering, informatics, and environmental sciences how to empirically verify the energetic and ecological efficiency of *farming* cryptocurrencies compared to traditional *mining*.

Accordingly, the following **research questions** were formulated:

1. What is the difference in electricity consumption between cryptocurrency mining and farming?
2. Can cryptocurrency farming be considered a more sustainable approach in terms of its carbon footprint?
3. What factors influence the economic return and environmental impact of both processes?

The methodology combines elements of **experimental measurement, economic analysis, and environmental assessment (Life Cycle Assessment – LCA)**. The experiment was conducted between **2022 and 2023** under laboratory conditions

within an academic network. Quantitative data were collected on electricity consumption, financial yield, and ecological balance.

The study was originally published as part of a bachelor's thesis in the *Teacher Training in Technology and Informatics* program [27].

The research adopted a **mixed-methods approach**, integrating empirical measurements, simulation modeling, and *Life Cycle Assessment (LCA)* of the utilized hardware.

This framework enabled not only a comparison of energy consumption but also an evaluation of **material and environmental factors** – including CO<sub>2</sub>-equivalent emissions, component lifespan, e-waste generation, and opportunities for secondary reuse of storage devices.

The methodology also included the development of computational models for Return on Investment (ROI) and Energy Efficiency Ratio (EER), which allowed the transformation of technical data into economic and environmental indicators.

In summary, the chosen approach combines **experimental measurement, life-cycle analysis (LCA), and comparative evaluation**. This multidisciplinary framework captures the technological, ecological, and economic dimensions of the studied problem, providing strong motivation for students in the fields of technology, informatics, and ecology, while fostering both theoretical understanding and practical competencies in these disciplines.

### 3.1 Experimental environment

The research was conducted under laboratory conditions at the *Faculty of Science, University of Hradec Králové*, between **October 2022 and April 2023**. The setup was designed to simulate the real operational environment of both *mining* and *farming* systems.

Two devices were tested:

#### ***Mining setup for Ethereum (PoW):***

- **Hardware:** 5× AMD Radeon R9 390 (8 GB), AMD FX-8350 CPU, 16 GB RAM
- **Power consumption:** 780–820 W at 100% load
- **Software:** PhoenixMiner 5.9d, Nanopool network
- **Average operating temperature:** 72–75 °C

- **Estimated GPU lifespan:** 24 months
- **Cooling:** active
- **Operation mode:** continuous (24/7)

*Farming setup for Chia Network (PoST):*

- **Hardware:** 6× 10 TB Seagate Exos HDDs, 1× 1 TB Samsung 970 EVO SSD, Intel i5-10400 CPU
- **Power consumption:** 45–55 W during operation, up to 250 W during plotting
- **Software:** Chia Blockchain GUI 1.6.0
- **Average operating temperature:** 34
- **Estimated HDD lifespan:** 5 years
- **Cooling:** passive
- **Operation mode:** continuous (24/7)

Both systems were operated under identical climatic conditions, and power consumption was measured using *TP-Link HS110 smart wattmeters* with a **sampling interval of one minute**.

The measured parameters included:

- **Energy consumption (kWh)**
- **Device temperature (°C)**
- **Noise level and operational stability**
- **Number of computational blocks produced (system efficiency)**

### 3.2 Mathematical framework and analytical formulas

This section presents the mathematical model and computational procedures used to quantify the **energy, environmental, and economic performance** of the studied blockchain consensus mechanisms (*Proof of Work* and *Proof of Space and Time*). The analytical framework integrates *Life Cycle Assessment (LCA)* principles with economic performance indicators, enabling the translation of technical and operational data into measurable sustainability metrics.

To comprehensively assess the environmental impacts, the *Life Cycle Assessment (LCA)* method was applied in accordance with *ISO 14040* and *ISO 14044* standards. The following **life cycle phases** were evaluated:

- **Manufacturing phase – extraction** and processing of raw materials, production of GPUs/HDDs, packaging, and transportation;
- **Operational phase – electricity consumption**, cooling, and maintenance;
- **End-of-life phase – recycling**, incineration, or landfilling of components.

Emission factors for production and operation were derived from the *Ecoinvent 3.9* and *EEA (2024)* databases [15][28]. Total emissions were normalized to a **functional unit of one mined or farmed block** and expressed in **kg CO<sub>2</sub>eq**. The following criteria were used to evaluate environmental impacts:

- **Energy consumption (kWh/year);**
- **CO<sub>2</sub>eq emissions (t/year) - calculated** using an emission factor of *0.39 kg CO<sub>2</sub>/kWh* (EU average, 2023);
- **Electronic waste generation (kg/year).**

Economic indicators included:

- **EER (Energy Efficiency Ratio) - profit** per unit of energy (CZK/kWh);
- **ROI (Return on Investment) - investment** payback period in months;
- **OPEX (Operational Expenditures) - average** monthly operational costs.

### 3.2.1 Energy analysis and EER calculation

Energy consumption (*E*, kWh) was annualized and supplemented with economic data on costs (*C*, CZK) and revenues (*R*, CZK). Based on these values, *Energy efficiency ratio EER* was calculated according to the following formula:

$$EER = (R - C)/E \quad (1)$$

where:

- *R* is annual revenue from mining/farming in CZK,
- *C* is annual electricity cost in CZK,
- *E* is annual energy consumption in kWh.

The *EER* value expresses how much **net profit (in CZK)** is generated per **kilowatt-hour of energy consumed**. A higher *EER* indicates both greater **energy efficiency** and **economic performance**.

### 3.2.2 Economic return and ROI calculation

The methodology also included a simulation of the *Return on Investment ROI* under various scenarios of electricity prices and cryptocurrency exchange rates. For the ROI calculation, the model incorporated *Initial capital expenditures CAPEX* representing the acquisition of necessary hardware. The *Annual revenue R* from mining or farming was also considered, derived from actual measurement data and the market valuation of rewards during the observed period.

The formula used for *ROI*, as applied in the results section, is expressed as follows:

$$ROI = 12 * CAPEX / (R_0 - C) = 12 * CAPEX / (R_0 - pE) \quad (2)$$

where:

- *CAPEX* is initial investment in CZK,
- *R* is annual revenue in CZK,
- *C* is annual energy cost in CZK,
- *E* is annual energy consumption in kWh,
- *p* is energy price CZK/kWh.

The constant 12 represents the conversion from years to months, as revenues and costs are expressed on an annual basis, while the *ROI* is reported in months.

This indicator provides a comprehensive assessment of the **financial performance** of both systems, expressing the **payback period** for the initial investment under varying electricity price and market yield scenarios.

### 3.2.3 Data processing

Data were collected automatically through the *HWinfo* monitoring software and supplemented by direct measurements using a wattmeter. The results were averaged over

**24-hour intervals**, converted to **annual values**, and visualized using tables and charts. For data processing, *Microsoft Excel* was employed, while the *open-source tool OpenLCA* was used to calculate and normalize environmental indicators.

### 3.3 Validation and limitations

To enhance measurement validity, all devices were operated under identical conditions of temperature, ventilation, and runtime. The main limitations of the research include the relatively small sample size, the controlled laboratory environment, and the short observation period. While these factors may affect the generalizability of the findings, they nonetheless provide a reliable foundation for a **comparative analysis** of *Proof of Work (PoW)* and *Proof of Space and Time (PoST)* under conditions approximating real-world operation.

## 4 RESEARCH RESULTS

This section presents the empirical findings of the comparative analysis between *Proof of Work (PoW)* and *Proof of Space and Time (PoST)*. The results summarize key differences in **energy consumption, environmental impact, and economic efficiency**, derived from experimental measurements, LCA calculations, and financial modeling. All values were normalized to a one-year operational period and expressed in comparable units to ensure the consistency of cross-model evaluation.

Comparison of key indicators between PoW system and PoST system is shown in the Table 1.

**Table 1**

*Comparison of key indicators between PoW system and PoST system.*

<b>Indicator</b>	<b>(PoW)</b>	<b>(PoST)</b>
Initial Investment: <i>CAPEX</i> (CZK)	120 000	50 000
Annual income: <i>R<sub>0</sub></i> (CZK/year)	107 000	69 000
Energy price: <i>p</i> (CZK/kWh)	5	5
Energy consumption: <i>E</i> (kWh/year)	7008	480
Energy cost: <i>C</i> (CZK/year)	35 040	2 400
Energy efficiency ratio: <i>EER</i> (CZK/kWh)	10.27	93.75
Return on investment: <i>ROI</i> (month)	20	9
Carbon emission: <i>CO<sub>2</sub>eq</i> (tons/year)	2.73	0.19
E-waste (kg/year)	3.6	0.4

Operating temperature (°C)	73	34
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#### 4.1 Initial investment

The first step of the evaluation involved analyzing Initial investment *CAPEX* for both tested systems.

In the traditional *Proof of Work (PoW)* model, a high-performance GPU-based setup was required, along with adequate power and cooling infrastructure. The total investment was approximately  $CAPEX = 120\,000$  CZK, primarily including graphic cards (GPU), power supplies, and basic server components.

In contrast, the *Proof of Space and Time (PoST)* system required only storage devices (SSD/HDD) and standard computing hardware, resulting in a total investment of around  $CAPEX = 50\,000$  CZK.

Thus, the initial investment difference is approximately **-58%** in favor of PoST, confirming that *farming based on storage capacity* demands significantly lower capital investment compared to energy-intensive computing-based mining.

#### 4.2 Energy efficiency and consumption

Measured data revealed substantial differences between the two tested systems. The *average daily energy consumption* of the PoW setup was **19.2 kWh**, while the PoST configuration consumed only **1.3 kWh**.

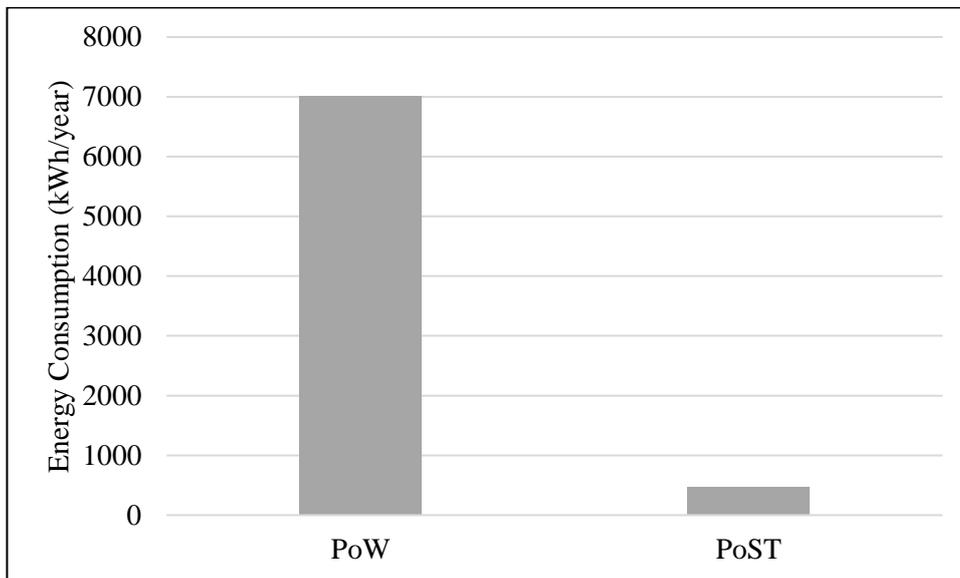
When extrapolated to annual operation (24/7), this represents total energy consumption:

- PoST system:  $E = 7\,008$  kWh/year,
- PoW system:  $E = 480$  kWh/year.

The magnitude of energy savings achieved by PoST compared to PoW is illustrated in Figure 1, which clearly demonstrates the *superiority of PoST* in terms of both environmental and economic efficiency. An energy reduction exceeding 90% constitutes a strong argument for the broader implementation of PoST in practice, particularly within the frameworks of ESG principles and Green IT initiatives.

**Figure 1**

*Annual energy consumption comparison for PoW and PoST consensus systems.*



In terms of Energy efficiency ratio *EER* – see Formula (1) in 3.2.1 section, the following values was achieved:

- PoST system:  $EER = 93.75$  CZK/kWh,
- PoW systém:  $EER = 10.27$  CZK/kWh.

This means that, at equivalent revenue, *farming is more than 9 times more energy-efficient*. These findings align with the study by Greenfield and Zhao [9], which reported energy savings between **90–95%** for PoST under comparable operational conditions.

### 4.3 Thermal profile and operational stability

Measured thermal profiles revealed another significant difference. The GPU-based PoW setup maintained an average temperature of **73 °C**, with peaks exceeding **80 °C**.

The PoST system operated within the **32–36 °C** range, requiring no active cooling. This parameter critically affects both device lifespan and operational reliability. While GPUs typically last **no more than 24 months**, HDD drives can reach **5–6 years** under stable conditions.

During the six-month testing period, *no operational interruptions* were recorded for PoST, whereas the PoW system required periodic maintenance (cleaning, fan

replacement, and thermal paste reapplication). From an operational standpoint, PoST is thus **significantly less maintenance-demanding**, which further enhances its long-term economic sustainability.

#### 4.4 Environmental impact

The *Life Cycle Assessment LCA* demonstrated that transitioning from PoW to PoST results in a dramatic reduction in the **carbon footprint**. Annual  $CO_{2eq}$  emissions were **2.73 t for PoW** and only **0.19 t for PoST** - a **93% reduction**. For PoW, 94% of emissions originated from energy consumption, whereas for PoST, most emissions were associated with the manufacturing of storage devices (primarily HDD and SSD). Although the overall *environmental balance* of PoST is positive, material recycling remains a key area for improvement.

The LCA also evaluated secondary environmental indicators:

- **E-waste generation:** PoW = 3.6 kg/year, PoST = 0.4 kg/year
- **Primary material use:** PoW = 28.2 kg, PoST = 5.1 kg
- **NO<sub>x</sub> emissions (acidification potential):** PoW = 0.68 kg/year, PoST = 0.05 kg/year

The results clearly demonstrate that PoST exhibits a *markedly lower environmental footprint* across all examined categories. These findings are consistent with international studies [4][5], which report **energy savings of 90–95%** and **emission reductions up to 98%** for PoST compared to PoW.

#### 4.5 Economic return and financial performance

The annual income  $R_0$  from cryptocurrency operations was estimated based on actual yields observed during the testing period.

The average annual income reached approximately:

- PoST system:  $R_0 = 107\,000$  CZK/year,
- PoW system:  $R_0 = 69\,000$  CZK/year.

This difference results from the distinct **reward structures** of both systems – PoW produces higher gross returns due to computational intensity but at the cost of

significantly higher operating expenses, whereas PoST delivers lower absolute income but a far more favorable **revenue-to-cost ratio**.

Based on these values, the Return on investment *ROI* was calculated – see Formula (2) in 3.2.2 section.

The *ROI* analysis revealed that, despite lower immediate revenue per unit of time, *PoST* achieves substantially faster long-term returns due to its low operational costs. Assuming an average electricity price  $p = 5$  CZK/kWh and a stable cryptocurrency exchange rate, the estimated payback periods were as follows:

- PoST system:  $ROI = 9$  months,
- PoW system:  $ROI = 20$  months.

These results confirm that PoST not only improves environmental performance but also provides a significantly more sustainable economic model for blockchain operation.

#### 4.6 Sensitivity simulation of economic return and ROI calculation

The monthly *ROI* is calculated based on Formula (2) – see 3.2.2 section.

In Formula (2), the annual baseline revenue  $R_0$  was replaced by the simulated value  $R = mR_0$ , where  $m$  represents the *multiplier factor* reflecting the relative change in revenue under different market conditions.

This substitution allows the *ROI* model to dynamically adjust to **optimistic**, **realistic**, and **conservative** scenarios, providing a more accurate representation of investment performance across varying cryptocurrency prices and electricity costs.

Three scenario variants were modelled:

- **Conservative scenario:**
  - Cryptocurrency price reduced by a factor of  $m = 0.7$
  - Electricity price  $p = 7$  CZK/kWh
- **Realistic scenario (baseline):**
  - Cryptocurrency price corresponding to the experimental period ( $m = 1.0$ )
  - Electricity price  $p = 5$  CZK/kWh
- **Optimistic scenario:**
  - Cryptocurrency price increased by a factor of  $m = 1.3$
  - Electricity price  $p = 3$  CZK/kWh

These scenarios provide a comparative framework for assessing the sensitivity of *ROI* to fluctuations in both market value and energy costs.

The values of monthly *ROI* for the conservative, realistic and optimistic scenarios of the PoW model are presented in Table 2 and illustrated in a 3D surface graph in Figure 2.

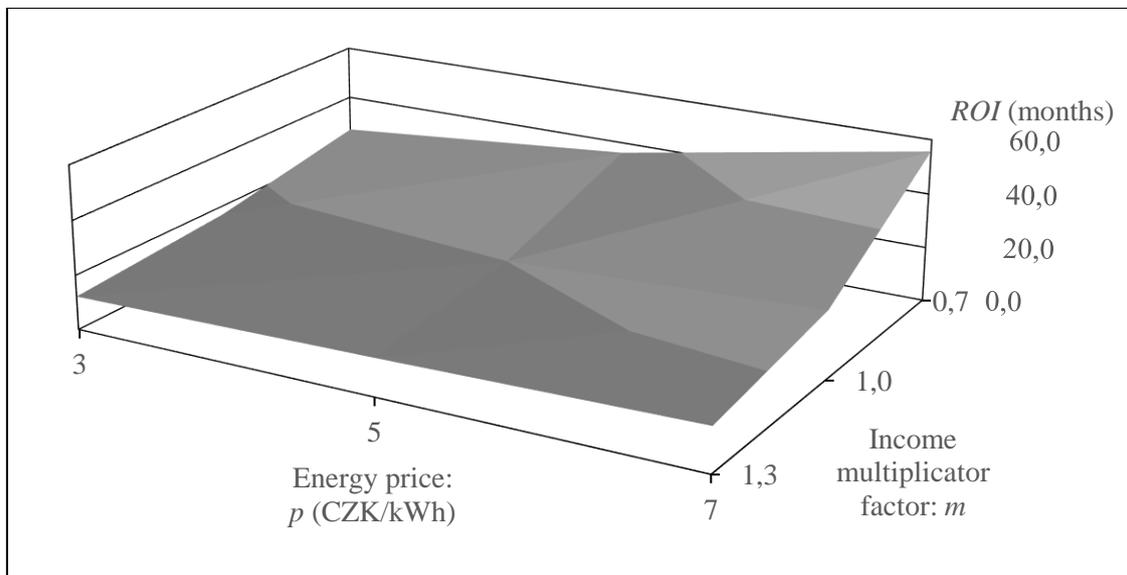
**Table 2**

*Development of monthly ROI values for the conservative, realistic and optimistic scenarios of the PoW model.*

PoW <i>ROI</i> (months)		Income multiplier factor: <i>m</i>		
		0.7	1.0	1.3
Energy price: <i>p</i> (CZK/kWh)	3	26.7	16.7	12.2
	5	36.1	20.0	13.8
	7	55.7	24.9	16.0

**Figure 2**

*3D surface graph of the monthly ROI development for the conservative, realistic, and optimistic scenarios of the PoW model.*



The values of monthly *ROI* for the conservative, realistic and optimistic scenarios of the PoST model are presented in Table 3 and illustrated in a 3D surface graph in Figure 3.

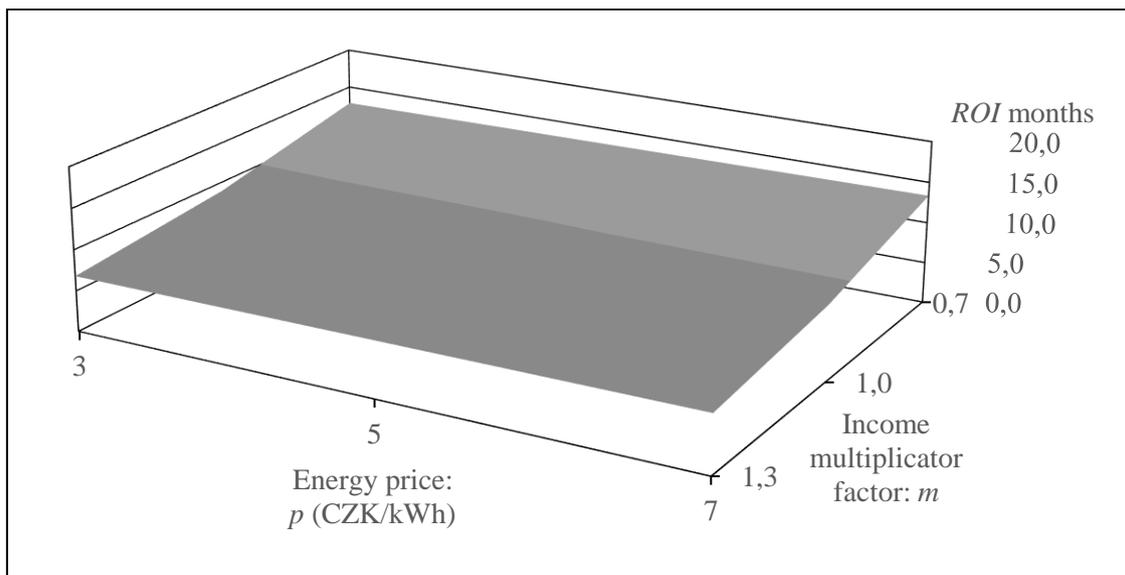
**Table 3**

Development of monthly ROI values for the conservative, realistic and optimistic scenarios of the PoST model.

PoST ROI (months)		Income multiplier factor: $m$		
		0.7	1.0	1.3
Energy price: $p$ (CZK/kWh)	3	12.8	8.9	6.8
	5	13.1	9.0	6.9
	7	13.4	9.1	6.9

**Figure 3**

3D surface graph of the monthly ROI development for the conservative, realistic, and optimistic scenarios of the PoST model.



From Table 2 and Figure 2, it is evident that the **PoW** model is highly sensitive to electricity prices. Under less favorable conditions, the return on investment extends beyond **3-4 years**.

In contrast, **PoST** demonstrates robust *ROI* performance across all modeled scenarios due to its low energy consumption. Even under the conservative scenario, *ROI* remains around **13 months**.

The sensitivity simulation confirmed that PoST remains profitable even with a 30% decrease in cryptocurrency value or a 25% increase in electricity price, whereas PoW

becomes economically unviable under such conditions. From an economic perspective, PoST can therefore be considered a more resilient and less volatile system.

## 5 DISCUSSION OF RESULTS

### 5.1 Comparison of PoW and PoST in the context of ESG criteria

To assess the sustainability of cryptocurrency technologies, the **ESG framework** (Environmental, Social, Governance) provides a comprehensive approach that evaluates not only direct environmental impacts but also broader social and governance dimensions.

A portion of this study's preliminary results was presented at the **DiVai 2024 Conference** [29], where a growing academic and industry interest in the environmental implications of blockchain technologies was confirmed.

Based on the measurements presented in the previous section, it can be concluded that **PoST** achieves a **substantial reduction in environmental burden**—over **90% energy savings**, a **93% decrease in CO<sub>2</sub>eq emissions**, and significantly **lower e-waste generation**. These empirical findings are consistent with those of **Greenfield and Zhao** [2] and **Chen et al.** [3], who identified similar ranges of efficiency improvement.

From the ESG perspective, the results of this research strongly support the notion of the **environmental superiority of PoST over PoW**. At the same time, PoST maintains a high degree of decentralization and accessibility, allowing for broader public participation in blockchain ecosystem. The PoW and PoST comparison in the context of ESG framework is summarized in Table 4.

**Table 4**

*Comparison of PoW and PoST in the context of ESG criteria.*

Criterion	PoW	PoST	Assessment
<b>Environmental</b>	Extremely high energy consumption (up to 120 TWh/year for Bitcoin); significant carbon footprint	Low energy consumption, but material burden due to SSD/HDD production and e-waste generation	PoST significantly better

<b>Social</b>	Concentration of mining in regions with cheap energy; low employment impact	Decentralized user participation, accessible to households	PoST slightly better
<b>Governance</b>	Strong decentralization but inefficient consensus mechanism	Higher efficiency, slight risk of data center concentration	Balanced

Our measurements therefore confirm that **PoST** performs significantly better than **PoW** in fulfilling the environmental and social pillars of the ESG framework. At the same time, the results highlight that material intensity of hardware remains a critical challenge. This observation is consistent with the findings of OECD (2025) [28], which recommends expanding ESG reporting to include Material Efficiency Metrics – indicators that account for the use of raw materials and the full life cycle of devices.

## 5.2 European legislative framework: MiCA and the Green Deal

In 2024, the European Union adopted the **Markets in Crypto-Assets Regulation (MiCA)**, introducing new obligations for cryptocurrency service providers. MiCA emphasizes transparency in energy consumption and the environmental impact of digital assets [12]. This marks the first legislative attempt to formally anchor the principle of environmental accountability within digital platforms.

According to our findings, mandatory disclosure of such data could significantly strengthen sector-wide environmental responsibility. This regulatory requirement directly corresponds with the results of our study, which demonstrated a substantial difference in energy consumption between **PoW (7008 kWh/year)** and **PoS (480 kWh/year)**.

At the same time, the **EU Taxonomy for Sustainable Investments** [20] and the **European Green Deal** [14] emphasize the reduction of greenhouse gas emissions across all industries, including the digital economy. In this context, cryptocurrency networks are viewed as part of a broader framework of sustainable digitalization.

Operators of crypto farms can gain a competitive advantage if they demonstrate the use of renewable energy sources, for instance solar panels, wind turbines, or waste

heat recovery systems. In practice, the concept of **Circular IT** is emerging, utilizing waste heat from computational processes for building heating [24].

This model is currently being tested in France, Sweden, and Germany, where projects such as Qarnot Computing and Heatbit integrate mining equipment into residential heating systems [25].

The findings of this research clearly indicate that PoST could serve as a practical tool for achieving these strategic sustainability objectives, particularly through its ability to reduce the carbon footprint by more than 90%.

### 5.3 Ethical and social implications

The ethical dimension of cryptocurrency technologies is often overlooked. Discussions tend to focus primarily on economic and technological aspects, while topics such as digital justice, energy solidarity, and social responsibility of computational systems are gaining increasing importance.

Our findings suggest that PoST, through its substantially lower energy demand, enables broader user participation and promotes the democratization of validation processes, thereby contributing to social equity within blockchain ecosystems. This observation aligns with the conclusions of [21], who emphasize the need to connect technological efficiency with ethical accountability among users.

Empirical results showing lower maintenance requirements and higher operational stability in PoST systems further reinforce the idea that this technology can be fairer and more accessible. From an ethical perspective, PoST represents a balance between performance and responsibility – reducing environmental impact while maintaining network openness and ensuring a more equitable distribution of rewards.

Unlike PoW, which tends to concentrate profits within a limited number of large mining pools, PoST supports a **participatory economic model** that empowers smaller participants and local communities.

In this context, cryptocurrency farming can be understood not only as a technological activity but also as a **didactic and ethical tool**, illustrating that even minor technological decisions such as the choice of consensus algorithm – can have significant implications for sustainability and social justice.

## 5.4 Technological trends and perspectives

The years 2023–2025 mark a significant shift toward **decarbonized blockchain** systems. Projects such as Cardano, Algorand, and Celo have declared carbon neutrality and the use of renewable energy sources (RES) for transaction validation [23]. Our results indicate that PoST has the potential to become a practical tool for achieving these objectives, as its energy consumption is approximately 93% lower than that of PoW. This finding aligns with the conclusions of De Angelis et al. [16], who emphasize that environmental efficiency can be achieved without major compromises in decentralization.

Another important trend is the recycling of computational heat, supported by both literature [24][25] and our empirical measurements. The thermal profile of PoST (34 °C) demonstrates that the technology can operate without the need for active cooling. This opens the way for concepts such as heat-reuse mining or circular data centers, where residual heat can be used for space heating. From the ESG perspective, this represents a unique example of circular digitalization (Circular IT), in which digital activity directly contributes to the sustainability of physical infrastructure.

In this context, it is worth noting the development of **hybrid consensus mechanisms** that combine the advantages of PoS and PoST. For instance, the Subspace Network employs a Proof of Storage and Stake (PoSS) model, which links storage capacity with the economic stake of validators [30]. A practical illustration of such an approach can be seen in the Cosmos protocol, which integrates Proof of Stake with Byzantine Fault Tolerance (BFT), achieving high efficiency while maintaining strong security [31]. This hybrid strategy may represent an ideal balance between energy efficiency, decentralization, and security.

Recent studies [16] further indicate that the **integration of PoST with Artificial intelligence (AI)** can optimize data distribution, predict hardware wear, and manage energy consumption based on the availability of renewable energy sources. Research in this direction will continue among students at the Faculty of Science, University of Hradec Králové.

### 5.5 Relations to the circular economy policy

The circular economy represents a key framework for the transition toward sustainable digital technologies. The results of our research indicate that while PoST dramatically reduces energy consumption, its environmental impact is partially shifted to the production and disposal phases of storage devices.

In the context of cryptocurrencies, this signifies a shift from the traditional linear model *take–make–dispose* to a *reuse–repair–recycle* model. In practice, this may involve extending the lifespan of mining hardware, refurbishing GPUs and SSDs, or repurposing HDDs for data archiving.

Empirical data on electronic waste generation (0.4 kg/year for PoST compared to 3.6 kg/year for PoW) suggest that well-designed recycling processes can have a decisive effect on overall sustainability. Our findings therefore complement existing literature, emphasizing that a *green data center* is not defined solely by the use of renewable energy sources, but also by effective **lifecycle management** of hardware components.

According to this model, all computing nodes should utilize renewable energy, employ low-emission cooling systems, and have transparent plans for component disposal and recycling. This approach aligns with the **Digital Product Passport initiative** [26], which requires traceability of the origin and lifecycle of ICT equipment.

Consequently, PoST technologies can form the foundation of environmentally responsible computing infrastructures of the future.

### 5.6 Integration of sustainability into the educational process

The study of cryptocurrencies and their environmental impacts goes beyond purely technological concerns and has become an important topic in education focused on **digital literacy** and **environmental informatics**. As stated by study [20], an **interdisciplinary approach** that connects informatics, economics, ethics, and ecology leads to a deeper understanding of the relationship between technology and sustainability.

In this sense, cryptocurrencies represent an ideal educational tool. Within experimental activities, students can analyze energy consumption, monitor market developments, apply principles of computational ethics, and assess the environmental consequences of innovation.

This pedagogical approach supports the competences defined in the **European Digital Competence Framework (DigComp 2.2)** [22], particularly in the areas of *digital citizenship* and *sustainable use of technology*.

Practical experience with cryptocurrency farming provides an opportunity to demonstrate the principles of **Green IT** – the use of information and communication technologies in ways that minimize negative impacts on the climate. This approach fully aligns with the objectives of the **UN 2030 Agenda for Sustainable Development**, specifically Goal 12 (Responsible Consumption and Production) and Goal 13 (Climate Action).

### 5.7 The role of universities and research institutions

Universities play a crucial role in shaping responsible technological thinking. Their mission is not only to monitor technological trends but also to actively contribute to the evaluation of the broader impacts of digitalization.

At the University of Hradec Králové, where this study originated, a growing trend can be observed in the integration of sustainable digitalization topics into the curricula of teacher education and ICT-related courses. Students engage with concepts such as digital ethics, responsible computing, and eco-efficiency of algorithms, which help them understand digital technologies within a broader ethical and environmental context [21][20].

Through **project-based learning**, students can analyze concrete cases – such as the **energy balance of blockchain systems** or the **optimization of their operational efficiency**. This pedagogical approach demonstrates a meaningful connection between theory and practice while aligning with the recommendations of the European Green Education Framework, which emphasizes the environmental dimension of technical education.

### 5.8 Research limitations

Although the results demonstrate the high potential of PoST, several limitations of this study should be emphasized:

1. **Limited experimental scope** – The measurements were conducted under laboratory conditions with a limited number of devices. The results may therefore be influenced by specific hardware configurations, software settings, or local cooling conditions.
2. **Lack of long-term data** – The research assessed operational efficiency over a period of several months. Long-term factors such as disk degradation, cryptocurrency price fluctuations, and network difficulty adjustments were not fully incorporated.
3. **Incomplete material life cycle assessment (LCA)** – The environmental evaluation focused primarily on CO<sub>2</sub>eq emissions. Detailed assessments of toxicity, rare metal use, and raw material extraction impacts (e.g., cobalt, lithium) were not included.
4. **Economic variability** – The ROI simulations were based on current market exchange rates and electricity prices, whose volatility can significantly affect real-world investment returns.
5. **Social and ethical dimensions** – The study primarily addressed technical and environmental factors, paying less attention to broader social impacts, ethical acceptance, and adoption potential in developing countries.

These limitations indicate that future research should adopt a **multidisciplinary approach**, combining **technological, environmental, economic, and ethical** perspectives to provide a more comprehensive understanding of sustainable blockchain development.

## 5.9 Recommendations for practice and future research

Based on the results, several recommendations for future work can be formulated:

1. **Technological optimization** – development of more efficient plotting algorithms and intelligent disk performance management using artificial intelligence (AI).
2. **Recycling strategies** – implementation of programs for the refurbishment and recycling of HDD/SSD devices, including the introduction of extended producer responsibility (EPR) frameworks.
3. **Integration of renewable energy sources (RES)** – crypto farming operations should be linked to local renewable energy systems and energy storage solutions.

4. **Standardization of ESG metrics** – establishment of unified indicators for measuring the environmental impacts of blockchain projects.
5. **Educational integration** – development of educational modules focused on sustainable digital technologies and the ethics of computational systems.

From a research perspective, future studies should focus on **long-term life cycle assessment (LCA)** to monitor disk degradation, emissions throughout the entire life cycle, and environmental impacts of large-scale PoST deployment.

It would also be valuable to explore the integration of blockchain with smart energy grids and examine the potential of PoST for decentralized energy consumption management.

## 6 CONCLUSION

The research demonstrated that cryptocurrency farming based on the Proof of Space and Time (PoST) system represents a more energy-efficient and environmentally friendly alternative to traditional Proof of Work (PoW) mining. Empirical results and life cycle assessment (LCA) confirmed that energy consumption in farming decreases by 90–95%, while the carbon footprint is reduced by up to 93%.

PoST thus signifies a major qualitative shift toward sustainable blockchain technologies. While PoW represents a model of the past, associated with inefficient energy use, PoST points the way toward responsible and adaptive blockchains of the future.

However, this model cannot be considered entirely impact-free. The ecological burden is partially shifted from the operational phase to material intensity, specifically to the production and disposal of storage devices. This shift indicates that the environmental benefits of PoST must be assessed comprehensively – not only in terms of energy consumption but also with respect to the life cycle of the hardware used, its recyclability, and durability.

From a sustainable development perspective, PoST can be regarded as a compromise solution that effectively fulfills the environmental (E) and partly the social (S) pillars of the ESG framework but still requires optimization in terms of governance (G).

In the area of management and regulation, there is a lack of a unified framework for environmental reporting and certification of digital activities, which would enable more accurate comparisons between technologies. The European MiCA framework and other legislative initiatives represent an important step toward greater accountability in the cryptocurrency sector. Requirements for transparent energy consumption reporting and the disclosure of environmental data may stimulate the transition to technologies utilizing renewable energy sources (RES).

In combination with the EU taxonomy for sustainable investments [32] and the principles of the Green Deal, PoST is likely to be prioritized within green financing and investment portfolios in the future.

From an educational perspective, the topic of cryptocurrency farming has significant potential. It provides a practical opportunity to connect informatics, environmental science, and economics, thereby fostering interdisciplinary thinking among students. Experimental measurements, blockchain process simulations, and LCA analyses can be incorporated into teaching in informatics, environmental education, and economics.

As stated by studies [21] and [20], these forms of learning support the development of digital and civic competencies in accordance with the DigComp 2.2 framework and help students understand technologies within the context of responsible use.

A more sustainable form of cryptocurrency consensus is not merely a technical innovation but also a social responsibility. PoST demonstrates that digital transformation can proceed in harmony with sustainability principles if accompanied by responsible management, recycling, and education.

The future development of blockchain technologies should be guided by the principle of “less power, more efficiency” – seeking a balance between technological progress, economic viability, and environmental protection. In this context, PoST can be seen as a precursor of the green blockchain – a technology that integrates innovation, efficiency, and ethics into a single platform.

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### **Authors' Contribution**

Both authors contributed equally to the development of this article.

### **Data availability**

All datasets relevant to this study's findings are fully available within the article.

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