Bitcoin
Implications & Opportunities for Corporates and Investors considering ESG

as of 30th July 2025

Within the framework of the ESG Committee,
"Bitcoin as a business tool for sustainable practices",
Bitcoin Bundesverband has compiled this working paper.

Bitcoin
Bundesverband

Imprint

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Abstract

This discussion paper examines the growing relevance of ESG (environmental, social, governance) and SDG (sustainable development goals) frameworks in the context of sustainable corporate governance and analyses the transformative potential of Bitcoin as both a key technology and a financial instrument. In light of global challenges such as climate change, social inequality and economic uncertainties, the paper highlights the intersection between Bitcoin applications and the SDGs, demonstrating how the integration of Bitcoin can enhance corporate ESG strategies while contributing to the achievement of global sustainability goals.

In particular, it examines the opportunities arising from the development of Bitcoin across various industries such as energy and utilities, agriculture, waste management and IT infrastructure. In this context, Bitcoin is presented not only as a hedge against inflation and a store of value, but also as an innovative tool for optimizing payment processes, enabling transparent supply chains, supporting flexible business models such as payment streaming, and integrating sustainable energy and heat utilisation concepts.

The paper provides evidence that the use of Bitcoin technology – through the cross-sector integration of mining into energy, heat and grid stabilization systems – can make a significant contribution to the reduction of greenhouse gas emissions. This impact is not driven by regulation or subsidies, but rather by strong market-based and ecological incentives and technical efficiency.

The document also discusses relevant regulatory frameworks, with a particular focus on German energy legislation (§13 EnWG), and illustrates how companies can gain competitive advantages and mitigate financial risks through strategic Bitcoin adaptation. Specific application scenarios are examined to illustrate how Bitcoin can be effectively aligned with ESG and SDG criteria, enabling corporates to proactively address the demands of a sustainable transformation.

This discussion paper is aimed at decision-makers from business, politics and the financial sector who seek to understand and strategically exploit the opportunities and risks associated with Bitcoin integration within the scope of sustainable corporate development. It provides a well-founded basis for designing future-oriented business models that take equal account of ecological, social and economic aspects.

1 Introduction

At a time when sustainability and responsible corporate conduction move ever more in the spotlight of public attention and political discourse, the concepts of ESG (Environmental, Social, Governance) and SDG (Sustainable Development Goals) are becoming increasingly important for corporates, their customers, investors and political decision-makers. These frameworks serve as a guiding principle for shaping a sustainable future and addressing global challenges.

Much like the internet in the late 1990s and early 2000s fundamentally reshaped entire industries, Bitcoin holds the potential to transform existing business models and unlock new opportunities.

Bitcoin - a decentralised digital asset built on open-source blockchain technology, is increasingly being considered in this context, and is examined in detail throughout this paper.

Why the link to the Sustainable Development Goals (SDGs) and ESG (Environmental, Social, Governance)?

The United Nations has formulated 17 Sustainable Development Goals (SDGs) aimed at addressing global challenges such as poverty, inequality, climate change and environmental degradation. By aligning the potential applications of Bitcoin with the SDGs, we demonstrate how this technology can generate not only economic value but also contribute meaningfully to the achievement of global sustainability goals. This is particularly relevant for companies seeking to strengthen their ESG (Environmental, Social, Governance) strategies and actively assume social and environmental responsibility.

Urgency for companies

Bitcoin has the potential to transform existing business models and open new economic and technological opportunities. It is essential to distinguish between Bitcoin as a financial asset and Bitcoin as a key technology. Regardless industry or company size, corporates should promptly assess the need for a Bitcoin strategy, adaption plan or practical use case – so as not to fall behind in a rapidly evolving environment. The consequences could be significant financial and competitive disadvantages.

This paper discusses the opportunities and risks associated with adopting Bitcoin as a financial instrument and as a technological solution. It explores how Bitcoin can be meaningfully linked to the SDGs and analyses the implications for a range of industries. Furthermore, it provides concrete recommendations for developing a Bitcoin strategy – enabling companies to unlock its full potential, engage with the topic to early on, and position themselves strategically considering a sustainable transformation.

Bitcoin as a key technology for various industries

What began as a digital means of payment is rapidly evolving into a flexible instrument for solving a wide range of economic and social challenges. In particular, the use of Bitcoin in sectors such energy and utilities, agriculture, waste management, finance and IT infrastructure presents significant opportunities to optimise processes while simultaneously advancing sustainability goals.

Bitcoin as an Inflation Hedge and a Store of Value

With a fixed supply capped at 21 million units and a decentralized architecture, Bitcoin offers protection against inflation and currency devaluation. Companies can incorporate Bitcoin into their financial strategy to preserve capital and hedge against economic uncertainty. Its low barriers to entry make it accessible to businesses of all sizes, enabling broad participation in the global Bitcoin infrastructure.

1.1 Introduction of CSRD

The Corporate Sustainability Reporting Directive (CSRD) is an EU directive that mandates comprehensive sustainability reporting for companies. It significantly expands the scope of the previous Non-Financial Reporting Directive (NFRD) and introduces strict requirements for transparency and comparability of Environmental, Social and Governance (ESG) performance.

Who is affected?

- Large companies with more than 250 employees, more than €40 million in turnover or more than €20 million in total assets
- Listed SMEs (from 2026 onwards)
- Non-EU companies with turnover of more than €150 million in the EU

What must be reported?

Companies are required to diclose their sustainability strategy in accordance with the European Sustainability Reporting Standards (ESRS). Particularly relevant for Bitcoin-related business models are:

- ESRS E1 – Climate Change (energy consumption, CO_2 emissions, reduction measures)
- ESRS S2 – Supply Chain & Social Impacts (financial inclusion, human rights)
- ESRS G1 – Governance & Compliance (transparency, regulatory compliance)

Why is CSRD important for Bitcoin companies?

- Companies with Bitcoin exposure must integrate and evidence ESG criteria
- Mining companies and energy-intensive data centers must disclose verifiable CO_2 data
- Bitcoin can support sustainable energy projects, but its impact must be quantifiable and traceable

The CSRD shifts ESG from a voluntary framework to a binding regulatory obligation for companies and investors. Companies must take an active approach to manage and document their ESG strategy to meet the new reporting requirements.

As companies are increasingly facing mandatory sustainability disclosure – particularly under the new Corporate Sustainability Reporting Directive (CSRD) – it is crucial to consider the implications of Bitcoin through a regulatory lens.

This paper outlines how Bitcoin can be positioned in the context of ESG and SDGs and highlights the strategic opportunities for corporates.

2 ESG &SDG

2.1 ESG

ESG criteria (Environmental, Social, Governance) serve as a framework for assessing and evaluating corporate sustainability performance. Their purpose is to ensure that environmental, social and governance aspects are systemically integrated into corporate and investment decisions.

The ESG criteria are originated in 2004, when the United Nations published a landmark report entitled "Who cares Wins". The aim of this initiative was to promote the integration of environmental, social and governance factors into financial markets and to highlight the importance of these criteria for investment decisions.

Two key initiatives have played a pivotal role in the institutionalization of ESG principles:

- **UN Global Compact[1] (established in 2000)**
  A voluntary initiative calling on companies to align their operations and strategies with ten universally accepted principles in the areas of human rights, labor, environment, and anti-corruption.

- **Principles for Responsible Investment (PRI)[2] (launched in 2006)**
  An UN-supported initiative aimed at encouraging responsible investment practices, providing a comprehensive framework for integrating ESG factors into investment analysis and ownership decisions.

Defined by a comprehensive set of rules for measuring, analyzing, assessing and evaluating a company's sustainability performance against a backdrop of sustainable and ethical practices, ESG criteria are divided into three main components:

- **Environmental:**
  Focus on resource management, emissions and environmental protection

- **Social**:
  Focus on the social impact and responsibility of a company

- **Governance:**
  Focus on corporate structures, ethics and transparency

At its core, ESG aims to strike a balance between economic success and social responsibility. When considered across its three components, ESG consolidates the most critical aspects that drive the adoption of sustainable and responsible practices:

- **Sustainable** corporate governance
  ESG criteria provide a structured framework for assessing and improving companies' social, environmental and corporate governance responsibilities. They are designed to help understand and manage the impact of corporate decisions on the environment and

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[1] Integrate the Principles for Responsible Investment UN Global Compact

[2] A technical guide to ESG integration in equity investing PRI

society.

- **Risk management**
  Integrating ESG factors enables companies to identify and mitigate potential risks at an early stage. These include risks related to environmental damage, social unrest, or poor corporate governance.

- **Competitive advantage**
  Companies that successfully implement ESG criteria can enhance their brand reputation, strengthen customer loyalty and gain access to new sources of capital. Investors are increasingly interested in companies with strong ESG practices, which improve market positioning.

- **Social responsibility**
  ESG encourages responsible corporate conduct that goes beyond regulatory compliance. This includes fostering workplace diversity, upholding ethical business practices and a positive impact on the community.

- **Long-term value creation**
  By integrating environmental, social and governance factors into their corporate strategy, companies can not only maximise short-term gains but also generate long-term value for all stakeholders. This supports sustainable economic development and contributes to the achievement of global sustainability goals.

2.2 Bitcoin and ESG

With the introduction of the Corporate Sustainability Reporting Directive (CSRD), companies are required to disclose detailed information regarding their sustainability impacts. This includes, in particular, the energy consumption and carbon footprint associated with business activities involving Bitcoin.

ESG transparency will become a key factor, especially for companies with Bitcoin investments, mining activities or payment solutions. They will be required to:

- The level of direct and indirect energy consumption attributable to their Bitcoin-related activities
- Whether they use renewable energies in Bitcoin mining
- Which strategic measures have been implemented to improve ESG performance

The use of renewable energy in Bitcoin mining, integration into sustainable energy concepts and efforts to reduce waste heat can all have a positive impact on ESG rating. At the same time, companies are obliged to ensure transparency about their Bitcoin linked activities.

Environmental
Bitcoin is often criticised for its high energy consumption, particularly due to the energy-intensive proof-of-work (PoW) mechanism. However, this criticism requires a more nuanced perspective, as there are increasingly positive developments – driven by growing use of

renewable energy in mining - that demonstrate favorable economic, social and environmental impacts:

- **Decarbonisation potential**:
  Bitcoin mining is frequently criticised for its high electricity consumption. However, such criticism often overlooks a crucial factor: the source and location of the energy used. A growing share of global mining operations is deliberately relocating to regions with excess renewable energy, positioning Bitcoin mining increasingly as a tool for decarbonisation.[3][4] .

  Take Texas (ERCOT) as an example: Within one of the most volatile and decentralised electricity markets in the US, Bitcoin mining farms function as highly flexible demand-assets. They absorb surplus wind and solar power during periods of low demand and can curtail operations rapidly when grid stability is threatened. Mining companies such as Riot Platforms and Lancium actively cooperate with grid operators to support system resilience and enhance the utilization of renewable energy.

  Paraguay: Paraguay hosts one of the world's largest sources of hydropower - the Itaipú Dam. A significant amount of the energy generates is not fully utilised due to a lack of domestic consumers. International Bitcoin mining companies are deliberately locating in Paraguay to make economic use of this renewable surplus energy – without additional emissions.

  Ethiopia: Following China's blanket ban on mining, parts of the industry relocated to countries such as Ethiopia. The Grand Ethiopian Renaissance Dam (GERD) offers vast untapped hydropower potential. In this context, Bitcoin mining is viewed as an export-oriented service that monetises surplus green electricity into much-needed foreign currency—with a comparatively low environmental footprint.

  These examples illustrate that, with careful site selection, Bitcoin mining can not only operate on low-emission but also plays a valuable role in energy system management and regional development. It is therefore incumbent upon investors and companies to specifically choose mining providers and jurisdictions with demonstrable contributions to decarbonization and sustainable energy integration.

- **Increased efficiency**:
  Ongoing advancements in mining technology—particularly the deployment of energy-efficient ASIC miners (application-specific integrated circuits)—are helping to reduce energy consumption per mined Bitcoin. Companies such as Bitmain and Canaan are continuously developing more efficient hardware. Additionally, mining operators like Genesis Mining and Marathon Digital Holdings are increasingly using surplus or stranded energy that would otherwise remain unutilised.

- **Integration into energy grids**:
  Bitcoin mining farms, such as those operated by Riot Platforms in Texas[5], actively cooperate with electricity providers to make use of grid surpluses and contribute to

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[3] Cambridge Centre for Alternative Finance (2025): Cambridge Digital Mining Industry Report – First Edition, April 2025 (Chapter IV).
[4] See also: Riot Platforms, Inc. (2024): ESG Report – June 2024, Executive Summary via Crispidea (fee required).
[5] Texas paid bitcoin miner more than $31 million to cut energy usage during heat wave - CBS News

grid stability. This model enables surplus energy to be monetized economically – enhancing the overall efficiency of the energy system while simultaneously reducing its carbon footprint.

- **Actual energy consumption**:
  According to the latest primary data from the Cambridge Centre for Alternative Finance (CCAF), global Bitcoin mining consumed around 138 terawatt hours (TWh) of electricity per year as of 30 June 2024[6] . This equates roughly 0.54% of global electricity consumption.

  To assess the overall footprint in a broader policy context, it is useful to compare this figure to global primary energy consumption. According to the BP Statistical Review of World Energy 2023[7] , global primary energy consumption in 2022 totaled approximately 600 exajoules (EJ), equivalent to around 166,667 TWh. This means that Bitcoin mining represents just 0.08% of global primary energy consumption.

  These figures indicate that, while the Bitcoin network´s energy use is not negligible, it remains significantly lower than that of many traditional industrial sectors - such as global gold mining or the traditional banking system. For the ESG assessment, it is not only absolute consumption that is decisive, but also the source of energy, its geographical context, and its carbon footprint. These factors are examined in further detail below.

In summary, although Bitcoin mining entails substantial energy use, its overall consumption remains lower compared to industry sectors. Moreover, the industry is increasingly making progress in adopting renewable energy sources and deploying more efficient technologies – thereby actively reducing its environmental impact.

Social (social aspects):
Bitcoin can enhance access to financial services in regions underserved by traditional banking infrastructure, offering new pathways for financial inclusion and resilience.

- **Financial inclusion**[8] :
  In sub-Saharan Africa, many people use Bitcoin via mobile wallets to make cross-border payments – bypassing costly intermediaries, reducing both fees and processing time. Research conducted by the Technical University of Dresden confirms that mobile fintech services, including those using cryptocurrencies, significantly support financial inclusion in the region.

- **Support in crisis situations** [9][10] :
  During the economic crisis in Venezuela, Bitcoin served as a means for citizens to preserve the value of their savings amid hyperinflation and to receive international support. Peer-to-Peer platforms, such as Local Bitcoins enabled users to easily convert Bitcoin into local currency. Venezuela remains one of the most active countries in the

[6] Cambridge Centre for Alternative Finance (2025): Cambridge Digital Mining Industry Report – First Edition, April 2025.
[7] Energy Institute (formerly BP): Statistical Review of World Energy 2023. https://www.energyinst.org/statistical-review
[8] Mobile Fintech Adoption in Sub-Saharan Africa: A Systematic Literature Review and Meta-Analysis | TU Dresden
[9] Economic Consultancy
[10] https://www.reuters.com/technology/venezuelas-economy-regresses-crypto-fills-gaps-2021-06-22/

world in terms of cryptocurrency trading.

- **Strengthening individual freedom[11] :**
  For activists and individuals, Bitcoin can provide a secure and pseudonymous way for storing assets and receiving international support. The decentralised nature of Bitcoin enables to retain financial autonomy.

These aspects illustrate how Bitcoin can contribute to social sustainability by enhancing financial inclusion and supporting people in crisis-affected environments.

Governance
The decentralised architecture of Bitcoin presents opportunities for a more transparent and tamper-proof financial system:

- **Transparency and security[12] :**
  Blockchain technology enables immutable and traceable documentation of transactions. Corporates can have their financial flows verified publicly via the blockchain, thereby enhancing trust among investors and consumers. According to the German Federal Office for Information Security (BSI), blockchain offers a high level of security and transparency due to its decentralised structure and cryptography foundations.

- **Decentralisation[13]**
  The absence of centralised control helps to reduce systemic risks. In September 2021, El Salvador adopted Bitcoin as legal tender to reduce dependence on traditional financial institutions and promote financial inclusion. However, this status was reversed in December 2024 as part of negotiations with the International Monetary Fund (IMF)[14] .

These aspects demonstrate how Bitcoin's governance model can contribute to the development of transparent and resilient financial systems.

2.3 SDG

The Sustainable Development Goals (SDGs) [15][16] were adopted by the United Nations in 2015 as part of the 2030 Agenda for Sustainable Development. They comprise 17 goals that aim to address the most pressing global challenges and contribute to their resolution.

Fundamentally, the SDGs were designed to promote sustainable development on a global scale – balancing social, economic and environmental dimensions. They are directed at

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[11] ANGELICA_ALVES_THESIS_OCT_2019.pdf

[12] BSI - Blockchain

[13] Decentralisation: Companies between stability and disintegration

[14] El Salvador Made Bitcoin an Official Currency. Now It's Backtracking for IMF Loan. - WSJ

[15] THE 17 GOALS | Sustainable Development

[16] Sustainable Development Goals - European Commission

governments, businesses, and civil society alike, and emphasis the importance of international cooperation in achieving shared objectives.

The individual SDGs are defined as follows:

- **SDG 1 No Poverty:**
  The goal is to end extreme poverty worldwide and strengthen social protection systems to improve the standard of living for all people.
- **SDG 2 Zero Hunger:**
  Ensure sustainable agriculture and food security to eliminate hunger and malnutrition.
- **SDG 3 Good Health and Well-being:**
  Ensuring access to high-quality healthcare for all and promoting healthy lifestyles.
- **SDG 4 Quality Education:**
  Promote inclusive and quality education and promote lifelong learning for all.
- **SDG 5 Gender Equality:**
  End discrimination against and violence against women and girls and promote their full equality and participation.
- **SDG 6 Clean Water and Sanitation:**
  Ensure access to clean drinking water and sanitation for all, and sustainable water management.
- **SDG 7 Affordable and Clean Energy:**
  Ensuring access to affordable, reliable and sustainable energy.
- **SDG 8 Decent Work and Economic Growth:**
  Promoting sustainable economic growth, productive full employment and decent work.
- **SDG 9 Industry, Innovation and Infrastructure:**
  Build resilient infrastructure, promote sustainable industrialisation and foster innovation.
- **SDG 10 Reduced Inequalities:**
  Reduce inequalities within and between countries, through more equitable opportunities and distribution of resources.
- **SDG 11 Sustainable cities and communities:**
  Promoting sustainable, safe and inclusive cities and communities through climate-friendly infrastructure and housing.
- **SDG 12 Responsible Consumption and Production:**
  Promoting resource-efficient and environmentally friendly production and consumption patterns.
- **SDG 13 Climate Action:**
  Take urgent action to combat climate change and its impacts.
- **SDG 14 Life Below Water:**
  Protect and sustainably use the oceans, seas and marine resources.
- **SDG 15 Life on Land:**
  Protect, restore and sustainably use ecosystems, forests and biodiversity.
- **SDG 16 Peace, Justice and Strong Institutions:**
  Promote peaceful and inclusive societies, access to justice and build effective institutions.
- **SDG 17 Partnerships for the Goals:**
  Strengthen global partnerships and mobilise resources to promote the implementation of the SDGs.

The SDGs serve as a strategic framework for governments, organisations and companies to guide decision-making that supports sustainable development. The goals are interlinked, meaning that progress in one area often generates positive impact across on other areas.

2.4 Bitcoin and SDGs

Bitcoin can contribute positively to a range of the SDGs. Its most relevant contributions align with the following targets:

- **SDG 1 - No Poverty:**
  Bitcoin facilitates access to financial resources, particularly in regions with inadequate banking infrastructure. In Nigeria, individuals using Bitcoin to conduct business transactions that were previously impossible due to a lack of banking services. A study by Springer Publishing explores both the opportunities and risks of cryptocurrencies as a portfolio component for individuals.[17]

- **SDG 7 – Affordable and clean energy**
  Mining farms such as Genesis Mining in Iceland use geothermal energy sources to produce Bitcoin sustainably. However, academic research shows that Bitcoin mining could slow down the transition to a sustainable energy supply in the long term, as it consumes significant amounts of renewable energy which might be used differently in the way forward.[18] .

- **SDG 9 – Industry, Innovation & Infrastructure**
  Technological developments such as the Lightning Network are enhancing the scalability and efficiency of Bitcoin transactions, contributing to the evolution of modern payment infrastructures. These innovations support industrial development and foster the expansion of resilient, digital financial ecosystems.

These examples illustrate how Bitcoin can contribute to achieving specific SDGs by promoting financial inclusion, supporting sustainable energy use and advancing technological innovation. At the same time, it is crucial to address existing narratives, such as energy consumption and regulatory concerns, in order to unlock Bitcoin's full potential as a tool for supporting the SDGs.

Under the reporting requirements of the Corporate Sustainability Reporting Directive (CSRD), corporates that engage with Bitcoin must disclose which SDGs are positively or negatively impacted by its use. The following goals are of particular relevance:

- SDG 7 (Affordable and clean energy) – Companies can integrate Bitcoin mining into sustainable energy concepts.
- SDG 9 (Industry, innovation and infrastructure) – Blockchain technology can make processes more transparent and efficient.
- SDG 13 (Climate action) – Necessity of measuring emissions and integrating them into climate strategies.

[17] Bitcoin & Co: Cryptocurrencies for everyone?| SpringerLink

[18] UW/H study examines the environmental impact of Bitcoin mining - Witten/Herdecke University

2.5 Bitcoin's Energy Consumption – Emissions, Benefits and Evaluation Criteria

Bitcoin's energy consumption has been at the centre of public debate for years. Often, attention is focused on the absolute amount of electricity required for Bitcoin mining – frequently compared to the energy consumption of countries or entire industries. However, those comparisons are misleading and fail to capture the broader context. It is not the mere amount of energy, but rather the carbon intensity, system value and incentive structure that are decisive[19] .

A key aspect of the Bitcoin blockchain is that its energy expenditure is directly linked to security. The energy used in mining is not a by-product, but rather an integral and deliberate component of Bitcoin´s consensus and security model.

For a proper assessment, the focus should shift from total consumption to the source, purpose and systemic function of energy being used.

ESG aligned assessment dimensions:

- **Emissions intensity of energy**
  The decisive factor is the source of energy consumed. Renewable energy sources such as hydropower, wind and solar energy cause hardly any direct emissions, while fossil sources (e.g. coal) result in significant CO_2 emissions. One kilowatt hour from hydropower is therefore not equivalent – environmentally or climatically - to one kilowatt hour from coal.

- **System value**
  The curtailment of renewable energy is a growing challenge in electricity grids, particularly in Germany. Grid congestion and insufficient load flexibility often result in surplus wind and solar power being wasted, even though this energy is both climate-neutral and low-cost. Instead, plant operators must be compensated – an inefficiency that not only incurs considerable costs but also jeopardises the energy transition.

  To address this topic, $13 of the German Energy Industry Act (EnWG) was introduced on 29 December 2023. The "use instead of curtailment" (NsA) concept aims to activate flexible electricity demand at the local level—specifically in designated relief regions—where surplus power can be absorbed by controllable loads.
  Bitcoin mining facilities are particularly well suited for those applications. Mining equipment can be switched on or off flexibly, does not require a continuous supply and can be located in areas with frequent curtailment. In doing so, they reduce the economic cost of curtailment and make productive use of electricity would otherwise remain unused.

  Furthermore, the heat generated during mining process can be used for space or process heating – an element of cross-sector energy efficiency that can be exploited economically, particularly in industrial parks, swimming pools, greenhouses or

[19] https://www.lynalden.com/bitcoin-energy/

neighbourhood solutions – turning electrical "waste heat" into thermal utility, contributing to decarbonisation in other sectors.

In addition, a grid-friendly use in the context of Redispatch 2.0 framework is conceivable – for example, if mining loads are used to relieve grid stress in congested network areas. However, the primary system benefit of mining lies in avoiding curtailment, rather than in redispatch in the narrower sense.

- **Economic Incentive Structure**
  Bitcoin mining is location-agnostic and highly price-sensitive. Miners act as price-takers in the electricity markets and strategically relocate their data centres to regions where energy is permanently inexpensive and surplus. This results to the increasing exploitation of renewable residual electricity sources (e.g. flare gas, curtailment electricity) that would otherwise remain unused or be burned in a climate-damaging manner.

ESG Dimension	Relevance	Typical Key Figures
Energy Mix	CO_2 intensity depends on the proportion of renewable, consumed or surplus energy.	% EE quote, g CO_2e / kWh
Transparence	On-chain data + primary studies enable real-time monitoring – an advantage for ESRS E1.	location & consumption disclosure
System Benefits	Demand response, load shedding, waste heat and flare gas utilisation reduce grid and methane emissions.	GWh load shedding, t CH_4 avoided

- Electricity demand of the Bitcoin network ≈ 138 TWh
- Emissions ≈ 33–40 Mt CO_2 with a 52.4% sustainable electricity mix

The following key aspects will be revisited and explored in detail throughout this paper, each within its thematic context. At this point, they serve to provide a more nuanced perspective on the ongoing debate on Bitcoin's energy consumption and its proof-of-work consensus mechanism.

Economic Unviability of Fossil-Based Baseload Mining Sites

Due to rising CO_2 prices, stricter ESG requirements from capital providers, and the declining levelised cost of electricity from renewables, unsubsidised fossil fuel power plants are becoming increasingly uncompetitive in the mining sector.

- **Miners are price takers**: Mining hardware migrates to the lowest marginal electricity costs. Renewable surplus energy (e.g. seasonal hydropower in Bhutan) and
- **zero-cost residual flows** (flare gas in North America)

are permanently below the break-even threshold of modern ASIC miners (< € 60/MWh). At the same time rising CO_2 prices and the rising ESG-aligned capital costs further erode the profitability of fossil-based baseload generation. As a result, unsubsidized coal and gas facilities are becoming economically unviable for Bitcoin mining.

Comparison with the Traditional Financial System

A bottom-up analysis reveals that the traditional banking and payment infrastructure (including data centres, cash logistics, branch networks and ATM infrastructure) consumes around 264 TWh of electricity annually – roughly twice as much as the Bitcoin network [20][21] . The respective study finds that the carbon intensity per transaction in the banking system exceeds that of the Bitcoin network predominantly powered by renewable energy.

Climate-positive Leverage through Sector Coupling

The findings of this paper demonstrate how Bitcoin mining, as a flexible high-load application, enables sector coupling energy sector (Redispatch § 13k EnWG),

- Finance/Computing,
- Heat supply (waste heat utilisation) and
- surplus & residual energy (curtailment electricity, methane flaring).

The integration supports the reduction of grid costs, accelerates renewable investments and avoids direct greenhouse gas emissions – a potential key to a cost-efficient energy transition.

Methodological classification: Why Generic Energy Comparisons are Misleading

Headlines such as "Bitcoin consumes as much electricity as Norway" may be attention-grabbing but lack analytical depth.

- Different system boundaries – National balances include all sectors, Bitcoin reflects only a sub-sector
- Absence of utility context – kWh comparisons ignore the economic, social or safety-related value of energy use
- Carbon intensity – 1 TWh of hydropower ≠ 1 TWh of coal-fired generation.
- Marginal vs. average effect – Climate policy focuses on additional or avoided emissions, not at absolute energy consumption[22] .

Guiding Principles for ESG-Compliant Assessment of Mining Activities

1. CO_2 intensity per MWh (Scope 2).
2. Share of renewable or waste & surplus energy.
3. Flexibility metrics (load shedding GWh, peak shaving factor).
4. Transparency of location and consumption data.
5. Sector coupling benefits (avoided curtailment kWh, waste heat replacement GWh).

When assessed against these criteria, the energy consumption of proof-of-work can be understood not as a liability, but as both a security and climate asset. This classification, however, presupposes that miners consistently utilise low-carbon energy sources and adopt high-efficiency technologies.

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[20] https://docsend.com/view/adwmdeeyfvqwecj2
[21] https://alphanode.global/wp-content/uploads/2022/06/SSRN-id4125499.pdf
[22] https://www.iea.org/reports/net-zero-by-2050

3 Three Core Applications of Bitcoin in Corporate Context

The integration of Bitcoin into business processes is gaining momentum, not only from an ESG perspective, but also in terms of digital transformation and the emergence of new business models. Companies today are facing the challenge of enhancing efficiency, transparency and resilience, while simultaneously being called upon acting sustainably, contributing to the broader good of society.

Bitcoin offers a robust technological foundation based on openness, immutability and decentralisation. The focus extends beyond its role as a store of value or financial asset to the use of its underlying infrastructure in creating a trustworthy, tamper-proof and globally accessible infrastructure – ranging from payment processing and supply chain to energy management.

This chapter outlines specific areas of application and demonstrates how Bitcoin can be practically integrated into business operations. Understanding these potentials requires understanding of the technological characteristics and attributes to the Bitcoin protocol.

- **Decentralised network structure:**
  Bitcoin operates without a central authority – each participating node maintains and validates the same data. This decentralisation makes the system resilient to failures, political interference, and institutional censorship.

- **Digital scarcity and predictability:**
  The Bitcoin supply is capped at 21 million Bitcoin, encoded immutably within the protocol. This digital scarcity provides a predictable supply structure – an aspect that is increasingly relevant in treasury management, incentive structures and inflation hedging strategies.

- **Security via cryptography and network stability:**
  Transactions in the Bitcoin network are validated through the proof-of-work consens mechanism. Despite its energy intensity, this method offers a high level of security and integrity, safeguarding the network from manipulation and censorship – an increasingly relevant factor in geopolitically sensitive markets. In addition, the protocol´s built-in difficulty adjustment ensures that the network continually calibrates itself to available computational power, creating a stable and reliable link between digital systems and the physical world – anchored in energy and time.

- **Digital ownership via cryptographic signatures:**
  Transactions are based on mathematically verifiable signatures that prove ownership – without reliance on centralized registries or intermediaries.

- **Transparency, auditability and regulatory interfaces:**
  The Bitcoin blockchain is public, immutable and globally accessible. All transactions are traceable, enabling audit-ready and tamper-proof records of payments and asset transfers. This transparency is particularly valuable in the context of accounting, auditing and compliance. At the same time, the pseudonymity of wallet addresses requires a technical framework that is compatible with regulatory requirements such as KYC/AML.

- **Programmable logic with bitcoin script:**
  Through basic programmable conditions - such as multi-signature schemes (multisig) or time-based executions – corporates can automate processes, including payment

authorization, governance mechanism, or contractual enforcement.

- **Open-Source evolution via community governance:**
  Technological adjustments are managed through an open proposal and consensus process ("BIP process"), rather than by centralized institutions. This approach enhances technological independence and reduces systemic dependency and vendor lock-in.

3.1 Strategic Integration of Bitcoin into Corporate Finance

Introduction and Context

The integration of Bitcoin into corporate financial strategies is gaining increasing relevance. Bitcoin can serve as an instrument for hedging against inflation, enhancing capital efficiency and optimizing international payments. However, embedding Bitcoin within a corporate treasury strategy requires comprehensive risk management, as factors such as volatility, regulatory challenges and operational complexity must be carefully considered. Corporates that successfully navigate and balance these factors can position themselves strategically for the future in a changing financial environment.[23] [24] [25]

While Bitcoin is frequently discussed as a hedge against inflation and a store of value, it also offers broader financial and strategic utility. These include:

- Collateral for debt financing
- Optimisation of cross-border transactions
- Dilution protection in equity structures

In this context, Bitcoin contributes to the diversification of corporate finance, strengthens the capital base, and opens access to new markets.

The relevance of this use case spans multiple sectors and company sizes. Corporates with significant liquidity or exposure to inflation and currency risks may particularly benefit. In parallel, interest from sovereign entities and state-owned investment funds is growing – signaling a broader trend of institutional recognition and adoption.

3.1.1 Technical Basics and Implementation

Bitcoin is a digital asset based on Bitcoin blockchain technology with a maximum total supply of 21 million Bitcoin (BTC). This artificial scarcity is often cited as the foundation for Bitcoin´s long-term value preservation and its potential as a hedge against inflation.

From a financial strategy perspective, it is essential to understand Bitcoin´s technical characteristics and operational implications. Strategic integration requires dedicated know-how to ensure secure custody and seamless usage. Key components include:

- **Transaction processing via a decentralised network:** Bitcoin transactions are executed directly between participants without central intermediaries. Transactions are cryptographically secured and permanently recorded on a public blockchain. This trust-

[23] The Strategic Bitcoin Reserve: A Hedge Against Inflation or Digital Mirage? by David Krause: SSRN

[24] The Bitcoin Ecosystem: 2024 Annual

[25] Enable digital innovation in the financial sector; preserve financial stability

minimised transaction system enables financial transfer independent of traditional finance infrastructures.

- **Digital scarcity:**
  The hard-coded maximum supply of 21 million Bitcoin creates a form of digital scarcity. This cap is technically immutable, giving Bitcoin deflationary characteristics and unique monetary profile among digital and traditional assets.

- **Custody:**
  Access to Bitcoin is secured via cryptographic private keys, requiring strict key and access management procedure. In practice, different custody solutions are used depending on risk appetite:
    - Self-custody using hardware wallets or multi-signature solutions
    - Institutional custody services with regulatory oversight and insurance coverage

  These solutions must be embedded within corporate policies on IT security, risk management and internal controls.

- **Transactability and liquidity access:**
  Bitcoin can be transferred globally, 24/7, without intermediaries. Its peer-to-peer architecture enables direct value transfer without the need for clearing houses, allowing international payments, intra-group liquidity management and real-time treasury operations.
  In addition, Bitcoin is highly liquid and can be converted into fiat currencies on major exchanges. Through APIs and institutional platforms, it can be seamlessly integrated into existing treasury systems.

- **Divisibility and capital flexibility:**
  Bitcoin is divided into eight decimal places, allowing even small amounts to be transferred or recorded with precision. This supports both granular allocation strategies and microtransactions within operational environments.

- **Speed and cost efficiency:**
  Especially for cross-border payments, Bitcoin transactions are faster and more cost-efficient than traditional bank transfers – particularly in cases involving large volumes or jurisdictions with inefficient banking infrastructure.

The integration of Bitcoin into treasury management requires specialised expertise to ensure secure custody and seamless operational handling. In addition, the accounting and tax treatment of Bitcoin remains complex and is subject to evolving legal frameworks in many jurisdictions. This complexity is largely due to the absence of a uniform legal and economic classification.

Existing regulatory and accounting frameworks were designed for traditional asset classes and often fail to adequately capture the unique characteristics of decentralized digital assets such as Bitcoin. The lack of classification as a distinct asset class, combined with ongoing technological developments and divergent international regulatory approaches, further complicates efforts to establish a standardized treatment.

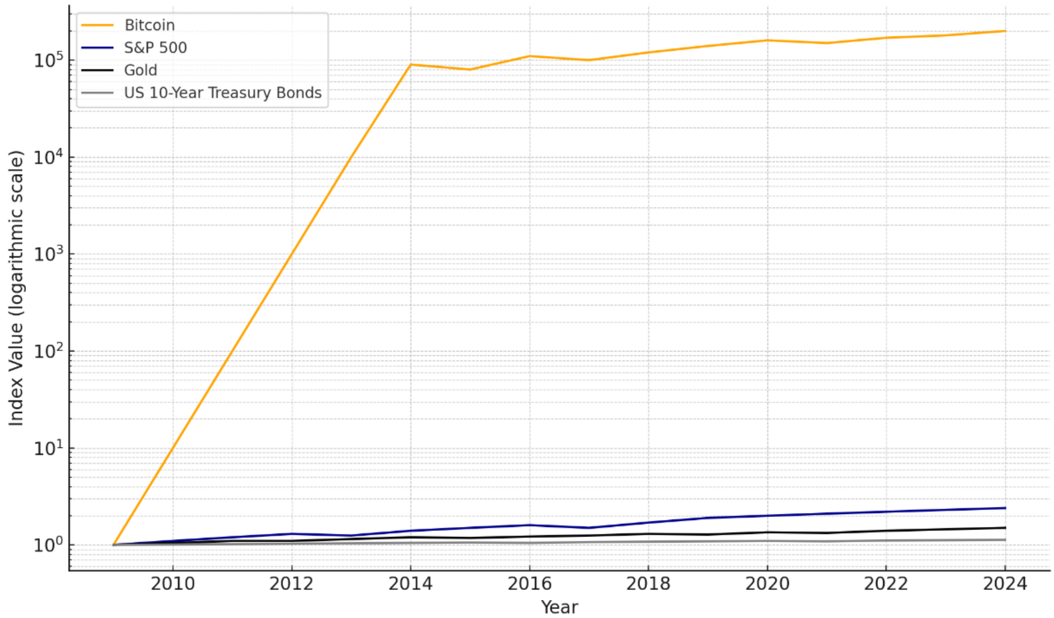
3.1.2 Economic Consideration and Market Dynamics

Companies that incorporate Bitcoin into their corporate treasury strategy pursue a range of financial and strategic objectives:

- **Inflation hedge and long-term value appreciation:**
  Due to its algorithmically fixed maximum supply of 21 million units, Bitcoin is considered as a scarce digital asset. This engineered scarcity, combined with its decentralised nature and increasing global demand, gives Bitcoin strong potential for long-term value appreciation. As a result, it is increasingly viewed as a store of value and a hedge against the loss of purchasing power caused by monetary inflation.

- **Strategic financing options and capital market access:**
  Bitcoin can be used as collateral for debt financing - for example to secure Bitcoin-backed loans. The growing acceptance of Bitcoin within capital markets enables corporates to access new forms of liquidity or optimise short- and medium-term cash structure through Bitcoin holdings. This can open alternative financing channels and improve capital structure, but it requires robust risk management due to Bitcoin's inherent price volatility.

- **Potential to enhance return on equity (ROE):**
  Over the past few years, Bitcoin has demonstrated a significantly higher compound annual growth rate (CAGR) than traditional asset classes such as equities, bonds or commodities. For companies allocating a portion of their equity or surplus liquidity into Bitcoin, may – if appropriately managed – contribute to a significant increase in return on equity.
  In a macroeconomic environment characterized by persistently low real interest rates, a Bitcoin allocation may represent a compelling addition to the company´s risk return profile. Ongoing valuation and exposure monitoring as part of treasury risk management framework is essential to mitigate downside risks and maintain strategic alignment.



CAGR – CUMULATIVE TOTAL RETURN 2009–2024[26] [27] [28]

- **Cross-Border payments:**
  The use of Bitcoin for cross-border payments offers advantages in terms of speed, cost

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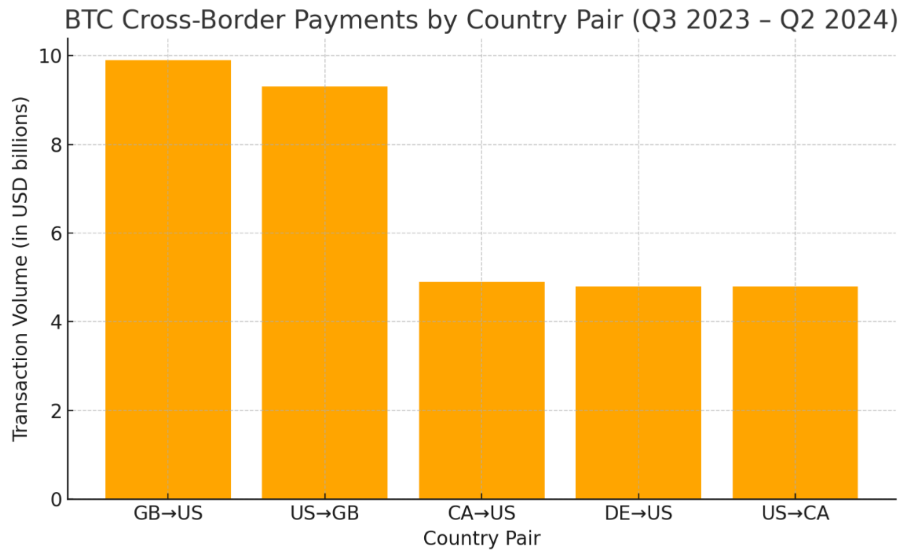
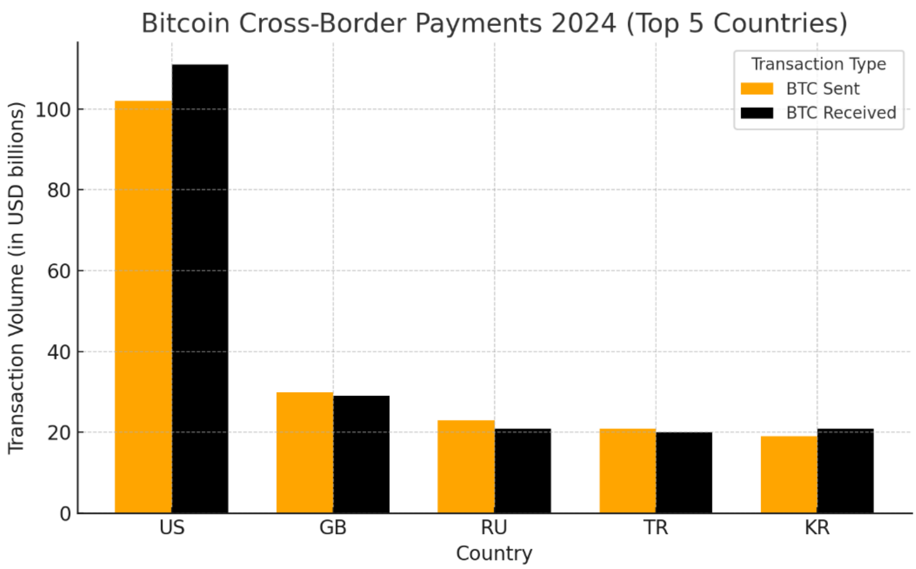
[26] https://www.slickcharts.com/sp500/returns/details
[27] https://www.macrotrends.net/1333/historical-gold-prices-100-year-chart
[28] https://fred.stlouisfed.org/series/DGS10

efficiency, and transparency. In many cases, it enables a reduction in both transaction costs and currency risk. Numerous studies confirm[29][30] [31] [32] the growing relevance of this application area, particularly in regions with underdeveloped banking infrastructure or high remittance fees.



Top 5 cross-border Bitcoin transaction pairs between Q3 2023 and Q2 2024.[33]



Representation of the five most important countries by Bitcoin payments sent and received in 2024.

- **Dilution protection:**
  Start-ups or growth companies can reduce their capital requirements for future financing rounds by allocating funds to Bitcoin. This approach helps protect founders

[29] https://www.bis.org/publ/work1265.htm

[30] https://hrcak.srce.hr/file/414855

[31] https://bvnk.com/blog/blockchain-cross-border-payments

[32] https://osl.com/hk-en/academy/article/how-bitcoin-is-revolutionizing-cross-border-money-transfers

[33] BIS Working Papers No 1265 DeFying gravity? An empirical analysis of cross-border Bitcoin, Ether and stablecoin flows

and investors equity and can a positive impact on the company valuation.

- **Reduced dependence on traditional financial systems:**
  Greater independence from banks and central institutions can be a strategically advantageous, particularly during periods of geopolitical and macroeconomical uncertainty.

- **Access to markets with limited banking:**
  Infrastructure: As a globally tradable digital asset not tied to any single national currency, Bitcoin can serve as a neutral unit of account and store of value – particularly useful in markets with unstable or depreciating local currencies.

- **Hedge against currency devaluation:**
  As a globally tradable digital asset, Bitcoin is not tied to any national currency. Bitcoin can serve as a neutral unit of account and store of value – particularly useful in markets with unstable or depreciating local currencies.

Market Examples and Institutional Adoption:

Corporates:

- **Strategy** (USA): Holds over 538,200 Bitcoin (as of 20 April 2025) as part of its diversification and inflation-hedging strategy [34][35] [36] [37] .
- **Tesla** (USA): Uses Bitcoin to diversify its corporate cash reserves[38] .
- **Genius Group** (USA): Hedging financial reserves with Bitcoin[39] .
- **Deutsche Börse** (Germany): Offers institutional Bitcoin investment through its Digital Exchange (DBDX)[40] .
- **Bitcoin Group SE** (Germany): Reports Bitcoin holdings on its balance sheet (February 2025), with a crypto reserve value of approximately €356.8 million[41] .
- **SynBiotic SE** (Germany): Has held part of its liquidity in Bitcoin since 2021 to hedge currency risks[42] .

Sovereign Funds and States:

- **Abu Dhabi:** The sovereign wealth fund Mubadala Investment Co. invested in BlackRock's iShares Bitcoin Trust in 2024 (investment value ~$436 million)[43] .
- **Bhutan:** The state-owned investment arm Druk Holding & Investments (DHI) holds approximately 13,000 BTC (since 2020) and is investing around USD 500 million with Bitdeer in green mining infrastructure[44] .

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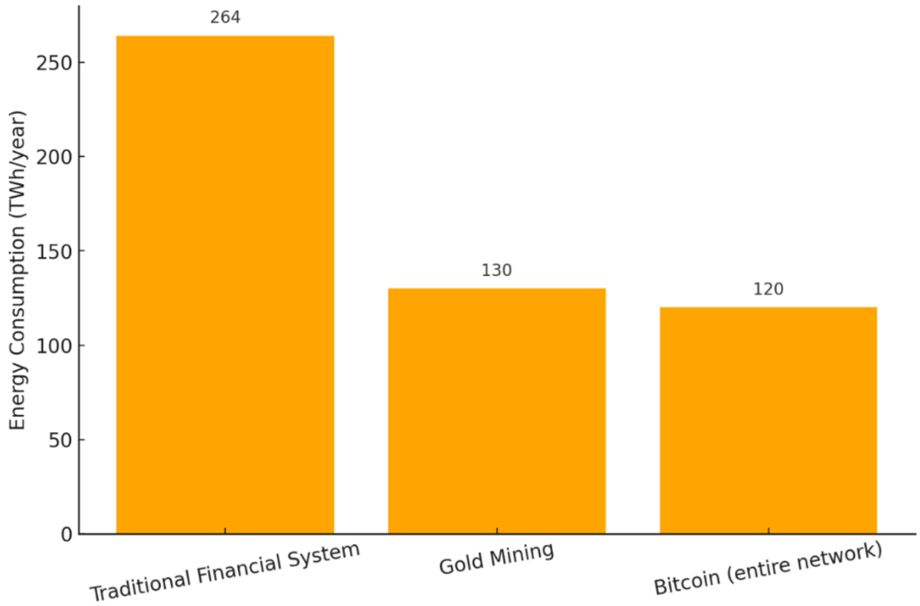
[34] https://www.investing.com/news/sec-filings/microstrategy-updates-atm-programs-and-bitcoin-holdings-93CH-3993337
[35] https://www.sec.gov/Archives/edgar/data/0001326801
[36] https://www.strategy.com/press/2025/02/24/strategy-btc-holdings
[37] https://www.reuters.com/technology/microstrategy-bitcoin-2024
[38] btc-echo.de: Institutional Bitcoin adoption in Germany
[39] wallstreet-online.de: Company invests in Bitcoin
[40] cryptonews.com: Bitcoin as an investment for companies
[41] https://www.eqs-news.de/bitcoin-group-se-2025
[42] https://www.synbioticse.com/de/presse/2021/crypto
[43] https://www.sec.gov/Archives/edgar/data/0001326801/mubadala2024
[44] https://www.kuenselonline.com/bhutan-bitcoin-mining-2023

- **Texas (USA): Advance Bitcoin** integration through legislative initiatives and pilot projects on state-level financial and energy policy[45][46] .

3.1.3 Environmental Aspects

Although Bitcoin is frequently criticised for its energy consumption, its relative share must be assessed in a differentiated manner compared to established systems. Studies indicate that the traditional finance sector – including banks, ATMs, payment networks and data centres – consumes significantly more energy than the Bitcoin network. Similarly, the annual energy expenditure associated with global gold mining exceeds the energy consumption of Bitcoin. Therefore, energy efficiency should not be evaluated in isolation, but rather in relation to the specific utility and function of each system.



COMPARISON OF ELECTRICITY CONSUMPTION IN 2024 [47][48]

3.1.4 Social and Governance Aspects

The social and regulatory landscape for Bitcoin remains highly fragmented across jurisdictions, creating both opportunities and uncertainties:

- **Regulatory uncertainty:**
  Regulatory requirements concerning the accounting treatment and taxation of Bitcoin vary widely across countries. While the European Union has introduced detailed disclosure obligations through the Markets in Crypto-Asset Regulation (MiCA), many other regions are still developing or refining their frameworks. This lack of harmonization hinders international comparability and may encourage regulatory arbitrage.

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[45] https://www.texas.gov/crypto-law

[46] https://www.fortworthtexas.gov/bitcoin-mining-pilot

[47] https://docsend.com/view/adwmdeeyfvqwecj2

[48] https://alphanode.global/wp-content/uploads/2022/06/SSRN-id4125499.pdf

- **Financial inclusion and access to global financial instruments:**
  Companies and individuals in regions with limited banking systems can benefit from Bitcoin by gaining access to global payments and financial services. This reduces currency and transaction barriers (SDG 8, SDG 10).

- **Corporate governance considerations:**
  Integrating Bitcoin into corporate treasury strategies requires clearly defined responsibilities, employee training and adjustments of existing corporate policies. This includes adapting internal governance structures to ensure proper oversight, transparency and control of this emerging asset class. Particular attention must be paid to delineating decision-making authority, , reporting obligations and control mechanisms to manage Bitcoin-related activities effectively and responsibly.

3.1.5 Opportunities, Risks and Outlook

From a financial perspective, Bitcoin offers several strategic opportunities for corporates, such as hedge against inflation, a means of portfolio diversification, a new financing instrument, a cost-saving tool for cross-border transactions and a way to reduce dependency on the traditional financial infrastructures. However, these opportunities require a thorough risk assessment, particularly considering the following factors:

- **Volatility:**
  Bitcoin's annualised realised volatility at 52.2% at the end of Q1 2025 requires active risk management and a clearly defined risk tolerance framework[49].

  Regulatory uncertainty:
  The globally inconsistent regulatory landscape adds legal and compliance complexity and may expose firms to jurisdictional risks.

  Operational complexity:
  Secure custody, wallet management and transaction execution require specialized technical and operational expertise. In addition, corporates must navigate accounting, reporting and tax complexities that are not yet standardized.

  Liquidity:
  Liquidity conditions vary significantly depending on the trading platform and market situation; the selection of exchanges and infrastructure partners is crucial to ensure efficient and reliable access to liquidity.

The long-term expectation is that institutional acceptance of Bitcoin will continue to grow steadily. This trend is already visible in the form of state-backed investments and treasury allocations by publicly listed corporations.

The development and scaling of sustainable mining models will further mitigate environmental concerns and facilitate deeper integration ESG-aligned strategies.

In summary, while integrating Bitcoin into corporate treasury frameworks remains a high-opportunity yet high-risk option, it can – when managed prudently – deliver strategic value through diversification, resilience and future-readiness.

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[49] NYDIG - Comparing Bitcoin and Gold

3.2 Payment Streaming, Pay-Per-Use Business Models and Autonomous M2M Transactions

Introduction and Context

Payment streaming and pay-per-use models are based on real-time billing for the actual usage of products and services. At the same time, machine-to-machine (M2M) transactions enable autonomous machines to transfer and receive value independently. This is particularly important in the industrial and IoT sectors, where autonomous processes and micropayments can give rise to new business models that do not incur disproportionately high transaction costs.

The strategic relevance of these concepts is considerable, as they apply across a wide range of industries that rely on usage-based services (e.g. Industry 4.0, media industry, mobility). Moreover, they are strong enablers of innovation and sustainable industrial development (SDG 9), as well as more efficient resource allocation and utilisation (SDG 12).

3.2.1 Technical Foundations and Implementation

The technical implementation relies on protocols that enable autonomous M2M transactions, as well as payment streaming mechanisms where payments are executed in real time and in very small units (micropayments). The core challenges are:

- Developing and integrating suitable protocols for exchange between machines or networked devices (IoT).
- Ensuring robust security measures, including encryption and authentication to prevent manipulation and misuse.
- Achieving scalability to support the execution of a high volume of micropayments in real time.

Industry standards and interoperable platforms play a key role here in enabling seamless exchange and in facilitating the efficient integration of new business models. These elements are essential to unlocking the full potential of usage-based services and autonomous payment ecosystems.

3.2.2 Economic Aspects and Market Potential

Pay-per-use business models and payment streaming enable companies to align costs directly with the actual usage of their products and services. This allows demand-driven customer payments while allowing businesses to manage revenue flows more accurately and respond flexibly to fluctuations in demand. Key benefits include:

- **More Flexible Billing Models:**
  Customers only pay for actual usage (e.g. in the media industry for individual articles or videos), without incurring the disproportionately high transaction fees that typically arise for micro-payments in traditional systems.

- **Lower Entry Barriers:**
  Usage-based pricing can be more attractive to price-sensitive customers, increasing market accessibility and unlocking new revenue streams.

- **Scalability:**
  Services can be offered globally, opening up new customer segments and supporting international expansion.

Key Industries affected:

- **Industry and Manufacturing:** machine & equipment leasing, production facilities & systems, Industry 4.0 applications
- **IoT Sector:** Connected devices, sensors, smart homes, smart cities infrastructures
- **Media Industry:** Newspapers, magazines, streaming platforms, music services
- **Mobility:** Car sharing, e-scooters, autonomous vehicles
- **Technology:** Software as a Service (SaaS), cloud-based services
- **Energy:** Dynamic tariffs for renewable energy supply

3.2.3 Ecological Aspects (Environment)

Usage-based models support more efficient consumption and production behaviour by enabling precise, real-time billing (SDG 12). For example, targeted billing based on actual usage can incentivize more efficient use of renewable energy and help avoid peak load periods.

Overall, pay-per-use concepts contribute to more conscious resource utilization and encourage sustainable consumption patterns – making them valuable tool in aligning business models with environmental goals.

3.2.4 Social and Governance Aspects

Social Aspects

- **Financial inclusion:**
  Usage-based payment models can improve access to essential services,particularly for price-sensitive customers (SDG 8).

- **Access to innovation:**
  By enabling machine-to-machine(M2M) transactions, even remote or in underserved regions can benefit from automated services - for example in agriculture or within smart city infrastructures.

Governance Aspects

- **Regulatory compliance:**
  Legal implementation requires adherence to financial, data protection and security regulations.

- **Company policies:**
  Transitioning to autonomous transactions demands clearly defined internal governance structures and risk management policies, ensuring that the deployment of such technologies operates within a transparent and secure framework.

3.2.5 Opportunities, Risks and Outlook

The introduction of payment streaming and M2M transactions holds significant transformative potential across a wide range of industries:

Opportunities

- **Real-time billing** enables precise measurement and monetization of resource and service usage.
- **Higher customer satisfaction** through tailor-made payment models.
- **Expanded access to global markets**, as micropayments enable international transactions without significant fee barriers.

Risks

- **Technological demands**:
  Implementation requires specific protocols and strong IT security.
- **Business models:**
  Companies may need to fundamentally adapt their processes, requiring significant investment and staff training.
- **Regulatory uncertainty:**
  The legal classification of autonomous transactions- particularly with respect to liability and data protection – remains unresolved in many jurisdictions.

In the long term, usage-based pay-per-use models and autonomous M2M transactions are expected to gain wider adoption. Their potential benefits in terms of innovation, resource efficiency and customer-centricity support growing acceptance across various sectors, from Industry 4.0 to the media and mobility industries[50] .

Examples

- **Industry 4.0:**
  Machines autonomously order and pay for spare parts or materials [51] .
- **IoT smart home:**
  Connected household devices automatically reorder consumables[52] .
- **Media industry:**
  Pay-per-article models allow users to pay only for individual pieces of content or media[53].
- **Mobility:**
  Autonomous vehicles independently pay for tolls, charging stations or parking[23].

3.3 Transparent Supply Chains

Introduction and Context

Transparent supply chains and logistics benefit greatly from blockchain technology and the integration of Bitcoin as an additional "trust anchor". Immutable and tamper-proof recording

[50] ecb.europa.eu: A big future for small payments? Micropayments and their impact on the payment ecosystem

[51] bankingclub.de: Industry 4.0 enables new business models"pay-per-use"

[52] corporatebanking.de: M2M payment: Autonomous payments between machines

[53] https://coincharge.io/en/bitcoin-micropayments-mit-lightning/

of supply chain events enhances the traceability and verifiability of products, improving efficiency and reliability across delivery processes. This holds transformative potential for sectors such as trade, manufacturing, logistics and the TIC industry (testing, inspection, certification).

Bitcoin can be applied not only for automated payment processing, but also as an "anchoring solution": certain process or product data (in the form of cryptographic hashes) are written to the Bitcoin blockchain, ensuring the integrity of such data can be verified globally.

However, it is important to note that this technology has proven most effective in clearly defined use cases and is less suites for large data volumes or high transaction rates.

3.3.1 Technical Basics and Implementation

- **Blockchain systems:**
  In many cases, hybrid approaches are applied. Critical data – such as timestamped hashes - are aggregated and periodically anchored to a public blockchain (e.g. Bitcoin). The underlying documents or data sets remain stored in external databases or a private blockchains.

- **Oracle problem:**
  To prevent manipulation or incorrect input, external data sources ("oracles") must be trustworthy. The Bitcoin blockchain ensures the immutability of the stored hash - not the factual accuracy of the referenced data.

- **Scalability and cost:**
  Given the limited transaction capacity of the Bitcoin blockchain and variable transaction fees, direct on-chain storage is only partially suitable for high-volume or real-time applications. Cost efficiency can be achieved though hash aggregation or second-layer solutions.

3.3.2 Economic Aspects and Market Potential

The use of blockchain and Bitcoin in supply chains and logistics offers significant cost savings through:

- **Increased efficiency and cost reduction**:
  Automated processes and a shared trust layer between suppliers, logistics service providers and customers can reduce transaction costs by eliminating redundancies and minimizing the need for intermediaries.

- **Competitive advantage:**
  Companies can respond to growing consumer demand for transparent supply chains, enhancing brand reputation and potentially commanding premium pricing for verifiably sustainable products.

- **Cost structure**:
  Initial Investment costs – such as infrastructure, staff training and system integration – are moderate to high. Ongoing on-chain fees (Bitcoin mining fees) can be reduced through hash aggregation, though they remain a critical factor as transaction volumes grow.

Moreover, companies gain a competitive edge in the global market, where demand for transparency and sustainability is increasing. In particular, the Testing, Inspection and Certification (TIC) industry can leverage blockchain and Bitcoin anchoring to develop new business models and reduce certification complexity and costs.

3.3.3 Ecological Aspects (Environment)

- **More efficient use of resources (SDG 12):**
  Transparent supply chain prevents duplicate transport and incorrect deliveries, thereby reducing fuel consumption and logistics inefficiencies

- **Reduction of counterfeiting:**
  Tamper-proof certifications can mitigate the risk of counterfeit goods, lowering waste and unnecessary production.

- **Energy consumption:**
  When Bitcoin is used as a trust anchor, it implies an indirect link to its proof-of-work mechanism. However, since only cryptographic hashes are typically recorded on blockchain, the energy footprint for the participating companies themselves remain relatively low.

3.3.4 Social and Governance Aspects

- **Transparency and consumer trust:**
  Tamper-proof documentation enhances consumer confidence in products, particularly in relation to fair-trade sustainability certifications.

- **Regulatory requirements:**
  - National and international data protection and data security regulations (e.g. GDPR) mandate that personal data must not be publicly accessible.
  - The legal recognition of blockchain-based certifications is still evolving in many jurisdictions, leading to legal uncertainty for international supply chains.

- **Oracle problem in practice:**
  In the TIC industry or at accredited testing institutions, data is verified before being anchored in the blockchain. As a result, the question of trust shifts to the competence and integrity of these entities.

3.3.5 Opportunities, Risks and Outlook

Opportunities

- **Improved efficiency and traceability** in supply chain processes through automated payments and transparent audit trails.
- **Strengthening brand reputation** and meeting ESG requirements via tamper-proof of origin.
- **Synergies with IoT applications** where devices can autonomously trigger transactions (e.g. automatic payment of freight or inspection fees).

Risks:

- **Costs and scalability**:
  Direct use of the Bitcoin blockchain becomes economically unviable for high transaction volumes or large data sets.
- **Oracle dependency**:
  Without trustworthy data inputs, even the best blockchain may store inaccurate information immutably.
- **Technical and regulatory complexity**:
  Companies must ensure legal certainty (e.g. certification standards, data security) and possess sufficient technical expertise.

Outlook:

Pilot projects and success stories in selected industries (e.g. food, pharmaceuticals, TIC) highlight the potential of blockchain and Bitcoin for supply chain transparency. However, a broader roll-out requires hybrid approaches to address the scalability and cost constraints. Oracles will remain a key issue: high data integrity still requires reliable and certified interfaces. Nevertheless, it is expected that more companies will adopt this technology to drive sustainability, traceability and process automation – including machine-to-machine(M2M) payment systems.

Examples:

- **Logistics**: Automated tracking and tracing of goods using blockchain, combined with Bitcoin payments for logistics services[54] .
- **TIC industry**:
  Certification processes for industries such as food, pharmaceuticals and other consumer goods, where data is documented in a tamper-proof manner. Bitcoin can also be used to automatically release payments upon verification[55] .
- **Retail**:
  Traceable production and delivery processes, e.g. in the area of fair-trade clothing, through the combination of blockchain and IoT[56] .
- **Manufacturing industry:**
  Real-time monitoring of material flows and automated Bitcoin payments triggered when predefined production milestones are successfully completed[57] .

3.4 Direct Crowdfunding and Financial Infrastructure with Bitcoin

Introduction and Context:

In recent years, new forms of crowdfunding have gained prominence within the crypto sector. Initial Coin Offerings (ICOs) and Security Token Offerings (STOs) emerged as token-based fundraising models in which project teams issue their own digital tokens to raise capital[58] . While ICOs were initially considered "transparent, secure and self-regulating" and capable of

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[54] DHL Freight: Blockchain in logistics

[55] PwC: Blockchain in the supply chain

[56] Capgemini: Blockchain transparency

[57] Softeq: Blockchain in supply chain management

[58] https://www.richmondfed.org/publications/research/econ_focus/2019/q1/feature2#

operating cross-border without government control, this assumption proved to be misleading. Many ICOs exhibited structural weaknesses, ranging from security vulnerabilities in smart contracts to centralised governance and speculative bubbles. In fact, most ICO tokens were later classified as securities, which lead to regulatory intervention and a collapse of the ICO market.

Against this backdrop, Bitcoin-focused crowdfunding is gaining attention - a model that does not rely on the issuance of new tokens but instead builds on Bitcoin´s existing infrastructure. Direct crowdfunding with Bitcoin allows supporters to fund projects directly in Bitcoin (BTC), often in the form of donations or pre-funding, without intermediary platforms or token issuance. Second-layer technologies such as the Lightning Network and sidechains such as Liquid are further enhancing the efficiency and global reach of this approach.

As the oldest and most decentralised cryptocurrency, Bitcoin offers a unique foundation for this model: a security architecture proven over more than 14 years, a global distributed and resilient network and a broad and diverse user base[59] .

The following section explores the market-shaping advantages of this Bitcoin-based crowdfunding in comparison to token-based models, outlining the technical and socio-economic implications – particularly with regards to financial infrastructure, capital allocation and transparency.[60] [61]

3.4.1 Technical Basics and Implementation

Bitcoin-based crowdfunding leverages the existing Bitcoin infrastructure and extends it into a decentralised financial infrastructure using second-layer protocols. Technically, funding typically occurs through direct BTC transactions to a project-related Bitcoin address or via the Lightning Network. Modern Bitcoin fundraising platforms such as TallyCoin and Geyser rely on non-custodial models: project initiators simply provide a personal Bitcoin address or an Extended Public Key (xPub) enabling all contributions flow directly into their wallet[62] . This way, fundraisers retain full control over the funds, and every Satoshi donated belongs directly to the recipient – the platform itself has no access to the funds and does not charge any fees.[63]

To support micropayments global microtransactions, the Lightning Network plays a central role. The Lightning Network is a Bitcoin-based second-layer solution that enables almost instant and low-cost transactions via payment channels[64] . Each Lightning transaction is ultimately secured by the Bitcoin blockchain but does not require immediate on-chain confirmation. In practice, campaigns receive donations via a Lightning invoice or a Lightning address. Platforms such as Geyser assign each project a dedicated Lightning address, allowing contributors to send funds directly from any Lightning wallet[65] . This increases interoperability and ease of use: a Geyser campaign can, for example, be funded directly from wallet apps such as Breez or via QR codes on social networks without requiring registration on the platform[66] .

[59] https://jimmysong.medium.com/why-bitcoin-is-different-e17b813fd947
[60] Framework of crowdfunding sustainable development goals projects using blockchain
[61] Does blockchain have a role in the financing infrastructure?
[62] Tallycoin Fundraising & Crowdfunding with Bitcoin and Lightning
[63] https://bitcoinke.io/2022/04/top-10-platforms-for-crowdfunding-in-crypto/
[64] https://bitcoinist.com/btc-the-lightning-network-s-energy-consumption-vs-the-world-a-comparison/
[65] https://bitcoinmagazine.com/business/crowdfunding-on-a-bitcoin-standard-with-geyser
[66] https://crowdsourcingweek.com/blog/lightning-network-crowdfunding/

In addition to Lightning, the Liquid Bitcoin sidechain is gaining traction in the crowdfunding context. Liquid is a federated second-layer network featuring 1-minute block times and confidential transactions. It enables the issuance of digital assets backed 1:1 by Bitcoin, making it suitable for regulated Security Token Offerings (STOs), such as tokenized shares, bonds or ownership certificates. Liquid provides fast settlement, privacy through confidential transactions and atomic swaps for trust-minimised trading.

Together, these technologies enable a decentralised financial infrastructure built on Bitcoin – allowing users worldwide to raise and manage capital without traditional banks. Technically, the entry barriers are low - anyone with internet access can operate a Bitcoin or Lightning node (e.g. via user-friendly solutions such as Umbrel) and effectively act as their own payment processor.

This open, modular architecture forms the basis for the economic and social advantages:

3.4.2 Economic Aspects & Market

From an economic perspective, direct Bitcoin crowdfunding offers fundamental structural advantages over token-based models in terms of security, decentralisation, incentive alignment and network effects.

1. **Security:**
   Bitcoin, as the oldest and most battle-tested blockchain, is secured by immense global computing power through its Proof-of-Work) consensus mechanism. It has proven itself *resilient against fraud and attacks.* In contrast, newly issued tokens often entail technological risks – complex smart contracts used in Ethereum-based ICOs have significantly increased the attack surface, as illustrated by high-profile incidents like the DAO hack[67] .
   Bitcoin deliberately limited scripting capabilities help reduce technical vulnerabilities. Furthermore, the absence of a central issuing authority lowers regulatory exposure, since Bitcoin is legally recognized as digital asset in many jurisdictions – unlike new tokens, which are often classified as securities.

2. **Decentralisation:**
   Bitcoin has no central authority, eliminating any *"single point of failure".* In ICOs control over token issuance and allocation is often retained by founding team or a single entity. Bitcoin-based crowdfunding is, by design, censorship-resistant: as a peer-to-peer network, it enables contributors to send Bitcoin directly to a project wallet without any intermediary - making it impossible for any central party to block transactions[68] .
   That was illustrated during the 2022 Canadian trucker protests, when authorities forced platforms like GoFundMe to shut down campaigns. In response, the community turned to Bitcoin donations via TallyCoin [69][70] .

3. **Game theory incentives and network effects:**
   In Bitcoin crowdfunding typically reflects long-term support for a project or a public good, rather than short-term speculation on token appreciation. As no new assets are created,

[67] The DAO Controversy: The Case for a New Species of Corporate Governance?

[68] https://bitcoin.org/bitcoin.pdf

[69] Canadian Truckers Are Funded with Bitcoin After $10 Million GoFundMe Campaign Was Shut Down

[70] Canadian trucker protest raises over £900,000 in bitcoin after GoFundMe blocks millions of dollars in donations

there is no artificial pressure to establish market value. Instead, contributed BTC flows directly into the project, strengthening the link between funding and outcomes. Supporters also benefit indirectly from Bitcoin's network effect: every useful application funded via BTC contributes to Bitcoin´s broader adaption, utility and potential value appreciation. Bitcoin´s global availability, widespread recognition and liquidity across all major exchanges significantly ease capital mobilization.

4. **Efficiency gains and cost advantages:**
   Lightning Network transaction fees are negligible, enabling viable micropayments even for extremely small amounts. In comparison, traditional crowdfunding platforms typically charge 5–10% in platform and payment processing fees. Platforms like TallyCoin charge zero commissions.
   On Geyser, donations are streamed in real-time directly to the project's Bitcoin node, increasing liquidity and operational flexibility. The "keep-what-you-raise" model particularly benefits smaller initiatives[71] - there is no requirement to hit a minimum funding threshold. Bitcoin´s public blockchain also fosters trust through built-in transparency and verifiability.

Finally, Bitcoin's global infrastructure provides access to markets that are not accessible through traditional financing. Cross-border capital allocation is seamless: while legacy crowdfunding platforms are often regionally restricted, Bitcoin-based campaigns can be supported globally. Examples such as Geyser, TallyCoin and OpenSats demonstrate that this model works - even in politically sensitive environments.

3.4.3 Ecological Aspects (Environmental)

The environmental debate around Bitcoin often centres on the energy consumption of proof-of-work mining. However, direct crowdfunding via Bitcoin and its second-layer technologies can be significantly more energy-efficient and resource-conscious on a per-transaction basis compared to alternative models.

- **Lightning transactions** cause virtually no additional electricity, as they are processed off-chain via existing payment channels. This allows the network to scale without a proportional increase in energy usage[72].

- **Sidechains such as Liquid** enable the trading of assets and tokenised instruments without writing every single transaction to the Bitcoin main chain. This relieves pressure on the base layer and improves the carbon footprint balance per transaction by reusing the existing security infrastructure.

- **The role of renewable energies:** Many mining operations are already relocating to regions with surplus renewable energy – which indirectly benefits crowdfunding projects, assuming that "cleanly" mined BTC serves as the underlying asset.

[71] https://github.com/OpenSats/website/

[72] BTC + The Lightning Network's Energy Consumption Vs. The World, A Comparison

Second-layer solutions such as Lightning significantly mitigate Bitcoin´s scalability-energy dilemma. Growing crowdfunding volumes can be achieved without proportionally increasing the environmental footprint.

3.4.4 Social and Governance Aspects

Bitcoin-based crowdfunding raises a range of social and governance considerations:

- **Social Inclusion:**
  Individuals in regions without established or functioning banking infrastructure can participate in global capital markets by using a Bitcoin wallet.

- **Censorship resistance and civil society:**
  NGOs, activists or journalists operating in repressive environments can turn to Bitcoin when traditional funding channels are restricted or blocked.[73] [74]

- **Community-driven governance:**
  In an open crowdfunding ecosystem, users determine which projects receive funding. Platforms such as Geyser use social validation mechanisms (e.g. a community-gated launchpad) to minimise the risk of fraud.

- **Reputation and transparency:**
  In the absence of a central authority, ongoing communication from project initiators about how funds are used is crucial to build and maintain trust. Multi-signature wallets or community-based decision-making processes can provide additional security and enhance legitimacy.

- **Social justice:**
  Bitcoin crowdfunding democratises access to capital. However, in unregulated markets it may expose inexperienced backers to elevated risks. The Bitcoin community is trying to mitigate this through education and voluntary ratings [75][76] , among other measures.

Overall, Bitcoin as a payment and infrastructure layer strengthens the financial sovereignty of both projects and supporters - by enabling new, decentralised forms of capital raising within the crowdfunding context.

3.4.5 Opportunities, Risks and Outlook

Opportunities

- **More open financing landscape:**
  Projects that previously had no access to venture capital or bank loans can now turn to a global community.
- **Establishment of a decentralised financial sector:**
  Platforms such as TallyCoin, Geyser and OpenSats enable a permanent crowdfunding

[73] Canadian truckers are funded with Bitcoin after $10 million GoFundMe campaign was shut down
[74] Canadian trucker protest raises over £900,000 in bitcoin after GoFundMe blocks millions of dollars in donations
[75] Bitcoin crowdfunding platform Geyser launches social-gated launchpad for Bitcoin projects
[76] https://opensats.org

ecosystem in which anyone can initiate, promote, and fund a project at any time and on their own terms.

- **Macroeconomic potential:**
  Initial initiatives such as El Salvador's proposed "Bitcoin Bond" demonstrate how sovereign bonds can be issued and managed within the Bitcoin ecosystem. If successful, Bitcoin could pave the way for private, corporate and sovereign financing.
- **Synergies with decentralised technologies:**
- Projects like Nostr (a decentralised social media network) illustrate how Bitcoin and the Lightning Network can directly support creator monetization through micro-donations, pre-sales, and investment products is often unclear and jurisdiction dependent.

Risks

- **Legal grey area:**
  Crowdfunding initiatives with profit expectations or significant capital volume could be considered a securities offering. The distinction between donations, pre- sales and investment products is not always a clear-cut.
- **Fraud risk:**
  Bitcoin transactions are irrevisible and pseudonymous, which complicates legal accountability and makes post-transaction remedies nearly impossible.
- **Volatility:**
  Bitcoin´s price can fluctuations present challenges for budgeting and financial planning in funded projects. Potential mitigations include Bitcoin-backed stablecoins or hedging strategies.
- **Technical requirements:**
  Lightning Network operations require sufficient channel liquidity and stable node availability – factors that can be problematic in regions with underdeveloped infrastructure.
- **Regulatory intervention:**
  If significant capital flows bypass government regulators may respond with stricter legal and tax frameworks.

Outlook

Current experience suggest that Bitcoin provides a viable foundation for a decentralised financial architecture. From a global perspective, this can enhance financial inclusion, reduce corruption and increase the efficiency of capital allocation. The long-term success of Bitcoin crowdfunding could deliver unique, market-shaping benefits: a transparent, secure and globally accessible funding mechanism that functions especially where conventional finance falls short – not through the issuance of speculative tokens, but through decentralisation, transparency and network effects.

3.5 Digitisation of Administrative Processes through Bitcoin Technology

Introduction and Context

The application of Bitcoin´s technology to secure administrative actions offers a pragmatic and highly secure method for ensuring integrity, transparency and global verifiability of public sector processes. In administrative systems - especially those subject to corruption, manipulation, or limited transparency - the immutability and decentralisation of Bitcoin can serve as a critical infrastructure layer for public trust.

While the relevance of this use case may be considered moderate in highly developed governance systems, it becomes highly significant in regions where institutional trust is fragile or state capacity is limited. In such contexts, tamper-resistant recording and global auditability can drastically enhance transparency, citizen participation, and legal certainty.

Use cases range from the timestamping of official documents, land registry entries, and judicial decisions to public tenders and voting records - any process in which verifiability, irreversibility, and auditability are essential.

3.5.1 Technical Basics and Implementation

Instead of storing sensitive documents directly on the blockchain, only a cryptographic fingerprint (hash) is typically stored. This hash serves a verifiable proof that a specific document or data entry existed in unaltered form at a particular point in time. The Bitcoin blockchain functions as a tamper-proof, decentralized time anchor, operating independently of national IT infrastructure or central authorities.

- **Core principle:**
  Only the hash is anchored, while the original data remains off-chain.

- **Technical resilience:**
  The Bitcoin blockchain has a high level of security and is resistant to subsequent manipulation or government censorship.

- **Practical implementation:**
  By bundling multiple hashes in a single transaction (batching), large-scale datasets can be integrated cost-effectively and with minimal blockchain resource usage.

Examples of successful implementations:

- **Estonia** (since 2012):
  The e-Government infrastructure uses the KSI Blockchain—a hash-based integrity system—which is regularly anchored to the Bitcoin blockchain to ensure global auditability[77] .
- **Georgia** (since 2016):
  Over 100,000 entries in the national land registry are secured using Bitcoin hashes, enabling global verification and increased trust in property rights.[78][79] [80] .
- **Guatemala** (2023):
  Election documents were secured via the OpenTimestamps protocol, ensuring tamper-proof and transparent electoral processes.[81][82] [83]

[77] Blockchain in public administration – Three successful examples from Europe
[78] Forbes – Republic of Georgia to pilot land titling on blockchain
[79] Cointelegraph – Georgia Records 100,000 Land Titles on Bitcoin Blockchain
[80] Exonum – Improving the security of a government land registry
[81] Bitcoin Magazine – How The Bitcoin Blockchain Is Fighting Fraud In Guatemala's Presidential Elections
[82] Open Dialogue Foundation – Bitcoin's Role in Guatemala's Digitally Safeguarded Democracy
[83] Nasdaq – Documentary Shows How Bitcoin Helped Verify Guatemala's Elections

3.5.2 Economic Aspects and Market

Market Potential and Relevant Sectors:

- **Public sector:**
  Registers, electoral authorities, asylum procedures.
- **International organisations and corporates:**
  Compliance, auditing.

Cost-Benefit Considerations:

- **Investment requirement:**
  Low to medium. The actual costs of anchoring via batch transactions is minimal (< £0.01 per document).
- **Primary cost drivers:**
  - Employee Training on cryptographic principles and secure data handling
  - Development or adaption of infrastructure
  - Adjustment to internal governance and process documentation
- **Access barriers:**
  - **Understanding of technology:**
    Requires foundational knowledge of cryptographic hash functions and timestamping protocols (e.g. OpenTimestamps).
  - **Market readiness and expertise:**
    Knowledge of implementing hash-based workflows and managing cryptographic evidence.

3.5.3 Environmental Aspects

A key argument is **cost and energy efficiency:**

- **Hash bundling:**
  Millions of data records can be secured with just a few Bitcoin transactions, which reduces the energy and resource consumption per document to a minimum.

- **Use of existing infrastructure:**
  Since only very few additional on-chain transactions are required, the added load on the Bitcoin network remains minimal.

As a result, the actual CO_2 footprint is relatively low in relation to the amount of data secured - especially compared to alternative solutions that require more extensive on-chain storage.

3.5.4 Social and Governance Aspects (social & governance)

Regulatory Requirements:

- Data protection (e.g. GDPR) requires that personal information is not stored directly on the blockchain; hashes themselves are not necessarily classified as personal data.

- Off-chain data storage must be reliable and secure so that only the hash is publicly visible on the blockchain.

Significance for Institutions and Society:

- **Transparency:**
  Public verifiability promotes accountability (e.g. in elections, register keeping).

- **Trust:**
  Citizens and international partners can independently verify the authenticity and timestamps of official documents.

- **International comparability:**
  Enables standardised, global insight into administrative processes, supporting SDG 16 (strong institutions) and SDG 17 (international partnerships).

3.5.5 Opportunities, Risks and Outlook

Opportunities

- **Integrity:**
  Immutable timestamps guarantee that documents or events existed at a specific point in time.
- **Resilience:**
  Protection against retroactive manipulation or censorship, especially relevant in countries with weak institutions.
- **Low costs:**
  Due to hash bundling, the cost per data entry remains extremely low.

Risks and Limitations:

- **No content verification:**
  The blockchain guarantees data integrity, not the correctness.
- **Scaling limitations:**
  Not suitable for real-time applications or high-frequency bulk processes.
- **Transparency conflicts:**
  Personal data must not be stored directly on the blockchain; implementation only possible through anonymised hashes.
- **Dependence on the bitcoin network:**
  Implementation requires governments to accept the decentralised governance model of a global blockchain.

Future Prospects:

- Successful applications in Guatemala and Georgia prove that Bitcoin-based integrity solutions can solve real-world challenges.
- The technology is expected to prove especially useful sensitive records or electoral documentation in contexts with low trust in central authorities.
- While the Bitcoin blockchain is not suitable for all digitisation projects, it can make a targeted and significant contribution to strengthening institutions and good governance

3.6 Integration into Energy and Grid Stabilisation Systems

Introduction and Context

Bitcoin mining can be used as a flexibly controllable load in power grids to actively contribute to grid stability and improved utilisation of renewable energy sources. This application, often referred to as demand-side response, enables the short-term ramp-up or ramp-down of electricity consumption in mining facilities. In this way, surplus electricity can be absorbed and grid bottlenecks relieved.

The relevance of this use case is considered highly relevant, as energy providers, data centres, large-scale industrial consumers, and regions with fluctuating power availability or high renewable energy input can benefit significantly.

3.6.1 Technical Basics and Implementation

A key practical example is the collaboration between the state-owned energy supplier Vattenfall in Sweden and proof-of-work mining facilities since 2019. Mining data centres (e.g. HIVE Blockchain in Boden) act as dispatchable loads in the Frequency Control Market (FCR), capable of shutting down up to 10 MW within seconds[84] . This stabilises the grid frequency and supports the flexibilisation of renewable energy systems.

Henrik Juhlin, former head of Physical Power Management at Vattenfall, pointed out in 2021 that Bitcoin mining represents an excellent flexible load. From a business perspective, the economic and climate-policy value of mining is particularly valid when powered by renewable electricity. According to Juhlin, banning Bitcoin mining in Sweden would be counterproductive, as the activity would simply shift to countries with higher CO_2 emissions [85][86] [87] .

Another example illustrates that Bitcoin mining facilities can be specifically deployed for grid stabilisation — both by quickly powering down and by absorbing surplus energy. In Norway, for instance, the shutdown of a mining farm in Hadsel caused public controversy despite low electricity prices[88] . This case exemplifies the complexity of load management at the intersection of market pricing, grid load and local politics.

A recent study[89] analyses curtailment dynamics in the mining sector across multiple countries confirms that flexible mining loads can positively impact power systems, provided they are integrated into the regulatory framework. The concept of "interruptible mining loads" is thus gaining importance, especially in grids with volatile renewable energy input. Furthermore, the waste heat generated during Bitcoin mining can be used, for example, to heat greenhouses or buildings or even to feed into district heating networks. Pilot projects in Switzerland (e.g. K51

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[84] Vatenfall enables industrial companies to participate in the Swedish FCR market

[85] HIVE Blockchain: Why hydropower from Sweden is used for mining

[86] Cyprtomonday.de – Vattenfall publicly defends Bitcoin mining

[87] Bitcoin Insider – Mining ban versus grid stability

[88] WiWo (2024): Why Norwegians are upset about the shutdown of a Bitcoin farm. https://www.wiwo.de/30000622.html

[89] Winkler, P. et al. (2024): Curtailment Dynamics in Bitcoin Mining and Grid Integration.

AG, RY3T) and Finland (e.g. Marathon Digital) demonstrate that Bitcoin mining can serve as a heat source in cold months and replace fossil fuels [90][91] [92] .

3.6.2 Economic Aspects and Market

Market Potential:

- **Energy suppliers:**
  Integration of mining facilities into redispatch and other grid regulation mechanisms.
- **Data centres and high-performance computers:**
  Use of mining flexibility to stabilise the power grid.
- **Industry:**
  Deployment as a controllable load and heat source in industrial environments.
- **Agriculture:**
  Heating of greenhouses with mining waste heat.
- **Real estate industry:**
  Cost-efficient heat supply for buildings.

Economic Benefits:

- Reduction of curtailments for renewable energy, as mining operations can absorb peak loads.
- Additional revenue for energy suppliers and operators by participating in frequency redispatch programs.
- Reduction of emissions and costs when fossil fuels are replaced by mining-generated heat.

3.6.3 Ecological Aspects (Environment)

The use of Bitcoin mining as a flexible load supports the expansion of renewable energies by utilising surplus electricity that would otherwise be lost (e.g. from wind or solar surpluses). This is particularly relevant in the context of SDG 7 (Affordable and clean energy), as it promotes more efficient utilisation of renewable electricity sources. In addition, the use of waste heat in line with SDG 13 (Climate Action), can replace fossil-based backup systems and thus improve the carbon footprint.

3.6.4 Social and Governance Aspects (social & governance)

Regulatory framework:

- A ban on Bitcoin mining, as discussed in the case of Sweden, could lead to relocation of operations to countries with higher CO_2 emissions.
- Grid operators and legislators must define clear guidelines for the use of mining facilities in redispatch or Frequency Containment Reserve (FCR) programs.

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[90] Smart Energy International - Blockchain mining supports the power grid

[91] Schaffhauser Nachrichten: Growing tomatoes with waste heat from servers

[92] International District Energy Association: How Marathon Digital is Using Bitcoin Mining to Heat a Finland Town

Social Significance:

- Integrating mining into energy grids can help stabilize networks and increase security of supply.
- Using renewable energy to support mining can increase public acceptance, as it contributes to achieving climate targets.

3.6.5 Opportunities, Risks and Outlook

The successful integration of Bitcoin mining into modern energy concepts is already a reality, as seen in Sweden and Switzerland. Proof-of-work facilities are increasingly evolving into technically controllable system components that can serve as a sustainable alternative to curtailing renewable electricity - within redispatch schemes, frequency containment reserve (FCR) and other regulatory instruments (e.g. §13k EnWG in Germany).

Opportunities

- Improved grid stability and more efficient use of renewable energy sources.
- Reduction of CO_2 emissions through heat recovery and the substitution of fossil fuels.

Risks

- Potential regulatory uncertainty in the event of politically motivated mining bans.
- Economic dependence on volatile Bitcoin prices and electricity costs.

In summary, Bitcoin mining can be integrated as a flexible load and heat sources into future-oriented energy strategies. Real-World implementations already demonstrate its potential to enhance the effectiveness of renewable energy systems while simultaneously ensuring greater grid stability.

3.7 Use of Surplus Renewable Energy for Bitcoin Mining and Heat Utilisation

Introduction and Context

The use of surplus energy from renewable sources for Bitcoin mining and subsequent heat utilisation is gaining increasing importance. One of the main drivers is the growing set of CSRD (Corporate Sustainability Reporting Directive) requirements, which mandates that companies involved in Bitcoin mining must document and verify their sustainable use of energy. This includes information on the source of the electricity, grid stabilisation measures using flexible mining capacities and the carbon intensity of the energy sources used, in line with ESRS E1.

A key application is the integration of Bitcoin mining into solar power systems or wind power projects; whereby surplus energy is utilized to increase the return on investment (ROI) and reduce energy costs - particularly when public feed-in tariffs expire. In addition, the heat generated during mining can be repurposed for heating systems, which increases energy efficiency and reduces heating costs.

3.7.1 Technical Basics and Implementation

When using Bitcoin mining for the consum of surplus energy, the focus is on integrating mining operations into existing energy and heating infrastructures. So-called mining heaters or mining boilers feed the waste heat generated during the process into building heating systems. In solar power plants or wind farms, these mining systems enable surplus electricity to be flexibly absorbed, which can also increase grid stability.

- **Heat utilisation:**
  The waste heat from the mining process is fed directly into the heating network via a heat exchanger or ventilation system.

- **Flexible load control:**
  Mining devices can be switched on to absorb power peaks; during low, they are throttled or shut down.

Examples include companies like 21energy and RY3T from Austria and Switzerland, which developing Bitcoin mining heaters[93] . Another provider, K51 (Switzerland), combines mining with high-performance computers to heat large-scale facilities or agricultural facilities [94][95] .

3.7.2 Economic Aspects and Market

The economic benefits arise from the dual use of surplus electricity and heat recovers:

- **Return on investment (ROI):**
  In solar installations, mining can generate additional income once government feed-in tariffs are no longer paid.

- **Scalable investment requirements:**
  A gradual expansion is possible, from initial deployment using small mining hardware units to larger industrial-scale applications.

- **Market potential:**
  High relevance for operators of solar and wind power plants, energy-intensive businesses that can use the excess heat, and for the real estate sector.

Access Barriers are relatively low:

- **Technological requirements:**
  Low to medium, as existing infrastructure (e.g. heating systems, power connections) can often be reused.

- **Investment required**:
  Low to medium, as mining hardware is scalable and modular.

- **Regulatory considerations:**
  Medium – tax regulations and potential required permits must be observed.

[93] 21energy.com
[94] k51.ch
[95] https://www.schweizerbauer.ch/regionen/ostschweiz/was-ein-serverraum-mit-einem-gewaechshaus-zu-tun-hat

- **Market knowledge and expertise:**
  Low; specialised service providers assist with planning and integration.

3.7.3 Ecological Aspects (Environment)

The concept of Bitcoin mining using surplus renewable energy and heat recovery can reduce energy waste and thus contribute to climate protection (SDG 13). At the same time, using the heat generated by mining reduces the demand for external heating energy, which can help cut emissions. Under SDG 7 (Affordable and clean energy) this falls under the more efficient use of renewable sources and waste heat.

From a CSRD (Corporate Sustainability Reporting Directive) perspective, companies can present this use case as a positive ESG factor, if they can demonstrate that the mining is predominantly powered by renewable energy sources and contributes to grid stability.

3.7.4 Social and Governance Aspects (Social & Governance)

The CSRD requirements clearly state that companies must provide evidence of their efforts toward sustainable energy use, such as:

- Proof of the origin of electricity (fossil vs. renewable sources).
- Documentation of carbon intensity in accordance with ESRS E1.
- Demonstration of how flexible mining capacities support grid stability.

This positions Bitcoin mining as a load management option.

From a governance perspective, companies must also consider tax-related and legal aspects of implementation (e.g. required permits), particularly in relation to integration into regional infrastructure and local regulations (e.g. building codes, energy laws).

3.7.5 Opportunities, Risks and Outlook

Opportunities

- Utilisation of previously unused surplus energy from solar or wind power projects.
  Reduction of heating costs and efficient energy use through integrated heat recovery.
- Improved ESG rating through documented, climate-friendly energy use and grid relief.

Risks

- **Price volatility** in the Bitcoin market, creating uncertainty regarding long-term profitability.
- **Regulatory aspects:** Permit requirements, tax aspects and energy related legislation may change.
  Technical complexity involved in integrating Bitcoin mining into existing systems and managing flexible load control.

Pilot Project – Mining Heating

A recent example is the Swiss company RY3T[96], which in late January 2025 successfully heated an entire single-family home using waste heat from a Bitcoin mining system. Initial data shows that a single mining heater can supply approximately 30–32 m² of living space. In the coming months, additional devices will be deployed to collect and publish representative operating data, including heating output, operating hours and solar power yield. These pilot projects illustrate the potential to efficiently utilise both surplus renewable energy and mining waste heat, marking a milestone in the evolution of sustainable energy systems.

3.8 Waste Heat Utilisation for Sustainable Heating Systems by Combining Bitcoin PoW mining with HPC (High Performance Computing)

Introduction and Context

The combination of Bitcoin Proof-of-Work (PoW) mining and high-performance computing (HPC) enables efficient waste heat utilisation for sustainable heating systems. PoW mining offers highly flexible load control, as it can be adjusted within seconds, while HPC is typically more profitable but less adaptable. A strategic integration of both methods allows for an optimal balance between flexibility and economic viability. This approach is particularly relevant for data centres, energy providers, industrial enterprises and the real estate sector.

3.8.1 Technical Basics and Implementation

- **PoW mining** requires only minimal internet bandwidth and can quickly respond to load fluctuations. This enables precise control of the heating curve and efficient use of surplus energy.

- **HPC** serves as the base load, ensuring continuous performance output. The resulting heat is constantly available but less adaptable to fluctuating demand.

- **Combination**: By smartly coordinating PoW mining and HPC, both variable heat demands, and energy availability can be addressed. PoW mining covers peak loads and HPC ensures constant performance, thus improving overall energy efficiency.

Examples of technical implementations include:

- **HeatCore (USA):** Offers combined PoW mining and HPC solutions designed for maximum flexibility and profitability[97] .
- **Northern Bitcoin AG (Germany):** Utilises mobile containers equipped with PoW mining and HPC units to directly repurpose waste heat heating applications [98][99] .
- **K51 AG (Switzerland):** Integrates high-performance computing with applications in greenhouses, hotels and industrial facilities. In a pilot project, immersion-cooled mining modules were used to heat a greenhouse [100][101] [102] .

[96] RY3T | BITCOIN HEATING
[97] https://heatcore.tech/2022/10/20/microbt-and-heat-core-inaugurate-first-hydro-cooling-and-heat-recovery-pilot-in-usa/
[98] https://de.cointelegraph.com/news/german-firm-unveils-mobile-eco-friendly-bitcoin-mining-containers
[99] https://via.ritzau.dk/pressemeddelelse/13596457/northern-data-ag?publisherId=90456
[100] https://www.shn.ch/innovation/k51-pilotprojekt
[101] https://www.k51.ch/news
[102] https://www.fachmagazin.ch/k51-bitcoin-mining-heizsystem

3.8.2 Economic Aspects and Market

- **Flexibility and Profitability:**
  PoW mining enables short-term load balancing, while HPC delivers higher returns as a stable base load.

- **Investment Requirements:**
  Low to medium. Scalable solutions allow for flexible entry and can be adapted to different needs (e.g. size of the heating application).

  Market Knowledge and Expertise:
  Available through specialised service providers and start-ups, keeping the entry barriers relatively low for operators.

- **Relevant Sectors:**
  Energy supply, real estate, industry, agriculture and data centres.

3.8.3 Ecological Aspects (Environment)

- **Sustainable energy and waste heat utilisation:**
  Replacing fossil fuels with waste heat from PoW mining and HPC operations, greenhouse gas emissions can be reduced.

- **SDG references:**
  - SDG 7 (Affordable and clean energy): Efficient use of renewable energy and waste heat.
  - SDG 9 (Industry, innovation and infrastructure): Promotion of innovation and improved energy efficiency in industrial processes.
  - SDG 13 (Climate action): Reduction of emissions through the partial or complete substitution of fossil energy sources.

3.8.4 Social and Governance Aspects

- **Regulatory requirements:**
  Compliance with applicable regulations for energy production and usage.

- **Access barriers:**
  - Technological requirements: Low to medium, as plug-and-play solutions are available.
  - Market knowledge: Service providers offer support, facilitating market entry.
  - Permits: Depending on the country or region, additional energy or building regulations may apply.

- **Governance:**
  Projects can enhance a company's sustainable and resource-efficient profile, positively contributing to ESG goals.

3.8.5 Opportunities, Risks and Outlook

Opportunities

- **Flexibility:** PoW mining can ramp up or ramp down very quickly.
- **Profitability:** HPC applications improve baseline utilization and revenue potential.
- **Efficiency:** Optimal use of electricity and waste heat reduces operating costs and emissions.
- **Scalability:** Both small-scale solutions (e.g. for residential blocks) and large-scale industrial projects are feasible.

Risks:

- **Price volatility:** Fluctuating returns from crypto mining can impact economic viability.
- **Regulatory developments:** Changes in energy or environmental regulations could complicate the business model.

Outlook:

With a growing focus on sustainable energy and cost efficiency, combinations of PoW mining and HPC are gaining importance. Pilot projects - such as K51 AG in Switzerland - demonstrate the potential of use waste heat from mining and HPC across sectors and replace fossil fuels.

4 Efficient Use of Surplus Power: Integration of Flexible Loads and Bitcoin Mining within the framework of §13k EnWG (Germany)

4.1 The Importance of Redispatch and the Approach under Section §13k EnWG

With the introduction of §13k in the Energy Industry Act (EnWG), Germany has established a new framework to minimise the curtailment of renewable energies (RE) and use surplus electricity efficiently. The implementation concept published by the transmission system operators (TSOs) on 1 April 2024 outlines how specifically activatable loads can be deployed to absorb excess power and relieve grid congestion Bitcoin mining fits seamlessly into this framework as it meets the core requirements of the TSO concept while offering significant potential for surplus power utilization. The following section explains in detail how Bitcoin mining can be integrated as a controllable load and highlights its relevance for the objectives of §13k EnWG.

The curtailment of renewable energy remains a major challenge for the German electricity grid. Grid bottlenecks often prevent the full use of electricity from wind and solar power, even though it is clean and cost-efficient. According to the Federal Network Agency, curtailment compensation costs amounted to €807 million in 2021, ultimately borne by consumers through grid charges. This inefficiency burdens the energy system and threatens the public acceptance of the energy transition.

Redispatch measures, which adjust the feed-in from power plants to prevent grid congestion, have long been a standard approach for grid stabilization. In 2023, a total of 27,133 GWh of feed-in was adjusted, of which 10,478 GWh came from renewable sources. Nevertheless, large volumes of curtailed energy remain that could be used more efficiently,

To address this issue, §13k of the EnWG was enacted on 29 December 2023. It focuses specifically on activating flexible loads. The "use instead of curtailment" (NsA) aims to absorb excess electricity and reduce the curtailment of renewable energy. The goal is to create new consumption capacities in so-called relief regions, which are identified based on historical curtailment data and grid analyses. The measures introduced by §13k EnWG make it possible to use previously wasted electricity in an economically viable and sustainable manner.

A particularly innovative approach in this context is the use of Bitcoin mining facilities as controllable loads. These systems meet the criteria of §13k EnWG and offer a flexible, scalable option for utilising surplus electricity. Additionally, they generate significant amounts of waste heat during operation, which can be used in district heating systems, further improving energy efficiency and sustainability.

The following section explains in detail how Bitcoin mining can be integrated into the redispatch system under §13k EnWG, what technical and economic advantages it offers, and what challenges must be considered. The relevance of these measures with respect to ESG (Environmental, Social, Governance) criteria and the broader energy transition will also be discussed. Sources include reports from the Federal Network Agency, studies by the German Energy Agency (DENA), and statements from the legislative process (e.g., Bundestag Doc. 20/9187)

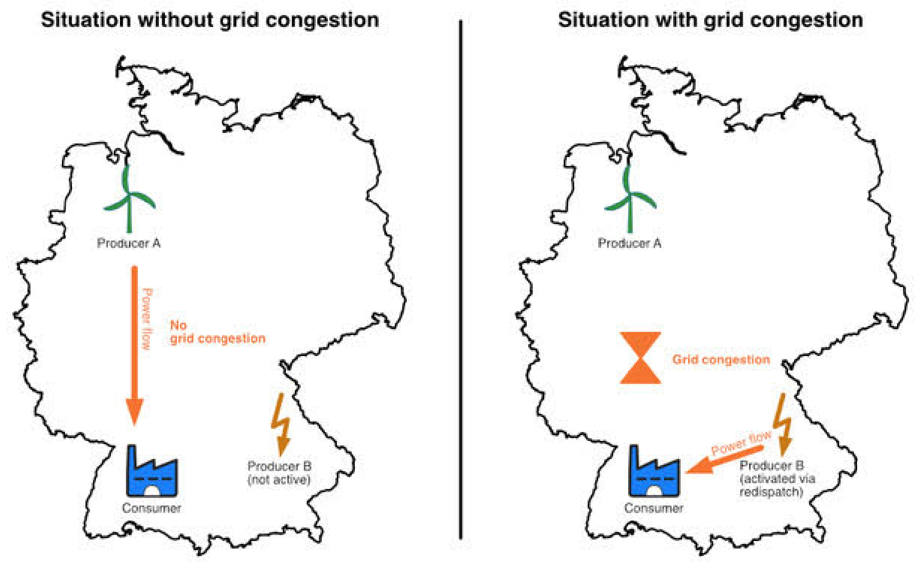
4.1.1 Introduction to the Issue of Curtailment Costs

On 29 December 2023, §13k of the German Energy Industry Act (EnWG) "Nutzen statt Abregeln"[103] came into force. Its aim is to activate

additional electricity consumption through controllable loads (so-called relief facilities) in suitable regions and thereby relieves grid congestion. This legal instrument is intended to reduce the curtailment of electricity from renewable energy plants caused by grid overload and to promote the efficient use of renewable electricity. The predecessor instrument, "Benefit instead of curtailment" (NsA 1.0), was already introduced with the Renewable Energy Source Act (EEG) 2016. The new regulation replaces and expands upon previous $13 (6b) EnWG, which came into effect in 2022 but was never practically implemented.

To implement the new regulation, several information and consultation processes were launched in 2024. The Federal Network Agency (BNetzA), the Federal Ministry for Economic Affairs and Climate Action (BMWK) and the transmission system operators (TSOs) held information sessions for industry associations, companies and distribution system operators. On 7 February 2024, the Federal Network Agency officially initiated the determination procedure[104] and conducted a public consultation from 15 April to 6 May 2024. Numerous associations, interest groups and companies submitted statements, which were acknowledged and published. These steps laid the foundation for the practical implementation of §13k EnWG.

The curtailment of electricity from renewable energy sources (RES) is one of the key challenges in the German energy system. Such curtailment occurs when grid congestion prevents the transport of surplus electricity. As a result, the electricity generated remains unused, while the plant operators are compensated for their lost feed-in tariffs in accordance with legal requirements. The resulting costs are passed on to consumers through grid usage charges.



SCHEMATIC OVERVIEW OF A SITUATION WITHOUT GRID CONGESTION AND A SITUATION WITH GRID CONGESTION AND REDISPATCH IN ACCORDANCE WITH SECTIONS 13(1) NO. 2 IN CONJUNCTION WITH 13A ENWG – FRONTIER ECONOMICS[105]

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[103] Grid transparency: benefits instead of curtailment

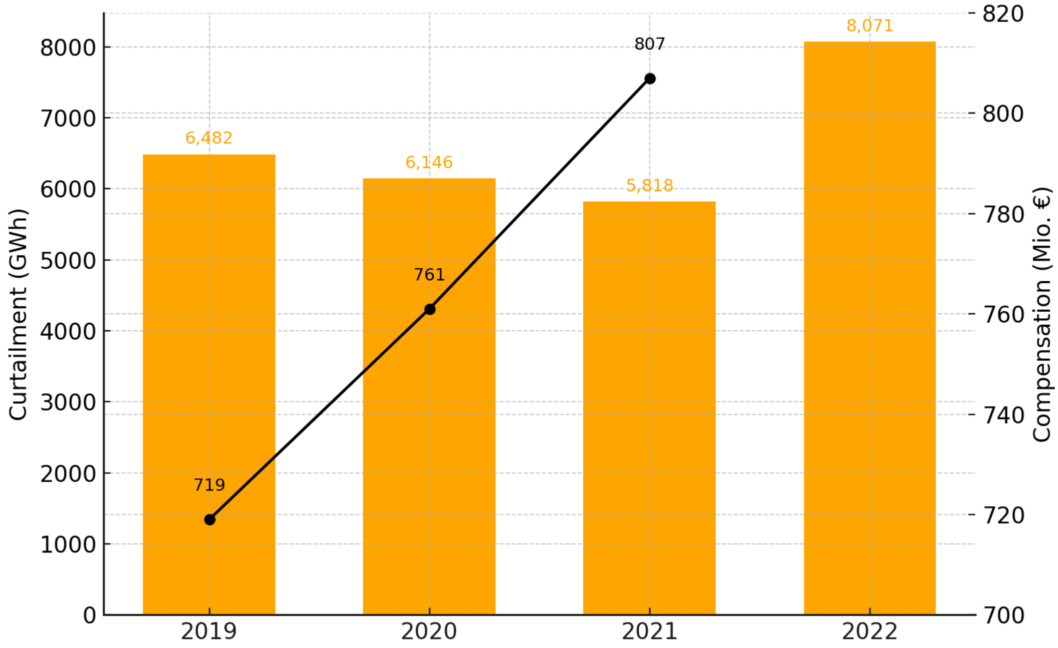
[104] Federal Network Agency Determination Procedure – Consultation 2024 Federal Network Agency: Determination Criteria

[105] Brief report for German transmission system operators (Amprion, Tennet, TransnetBW, 50 Hertz) Frontier Economics

A report by the Committee on Climate Protection and Energy[106] (20/9187) outlines in detail that curtailment costs have risen significantly in recent years. In 2021 alone, around 6.1 terawatt hours (TWh) of electricity from wind and solar plants had to be curtailed, resulting in compensation payments of around €807 million. These payments represent a significant financial burden for the energy system and are both economically and climate-wise inefficient.

The Federal Network Agency [107](Bundesnetzagentur) confirms these figures in its 2021report on grid congestion management. According to the report, approximately 5.8 TWh were curtailed, leading to the same €807 million in compensation.

This system causes consumers to bear the costs of unused renewable energy, which not only jeopardises public support for the energy transition but also drives up electricity prices for households and businesses.



COMPENSATION & CURTAILMENT
FRONTIER ECONOMICS BASED ON BNETZA / BKARTA, MONITORING REPORT 2023, TABLE 41[108]

Furthermore, the implementation plans pursuant to Section 13k of the German Energy Industry Act (EnWG), published by the transmission system operators (TSOs), points out the possibility of using surplus electricity from renewable energy (RE) systems more efficiently by deliberately creating additional loads in so-called relief regions.[109][110] . These regions were identified based on historical curtailment data, operational experience and grid planning factors. The aim is to reduce the curtailment of renewable electricity by enabling new consumption options such as electrolysers or other flexible loads.

[106] Committee report on climate protection and energy, printed paper 20/9187 Printed paper 20/9187

[107] Report by the Federal Network Agency on grid congestion management 2021 Link to BNetzA

[108] Federal Network Agency Monitoring Report 2023

[109] Implementation concept in accordance with Section 13k EnWG ÜBN implementation concept

[110] Relief regions dena Network Study III

The Committee on Climate Protection and Energy emphasises that the current system not only wastes financial resources but also jeopardises Germany's climate targets. Each curtailed gigawatt hour of renewable electricity from renewable sources represents a missed opportunity to replace fossil fuels and further reduce CO_2 emissions.

To address this issue, the concept proposed in §13k EnWG proposes a targeted integration of additional loads that can absorb the curtailed electricity in defined relief regions. This would not only reduce compensation payments, but also improve the efficiency of renewable energy utilization, thus contributing to the decarbonisation of the energy system.

A central approach of §13k EnWG is to reduce curtailment costs by actively deploying flexible loads. Surplus electricity should no longer be curtailed but instead used by consumers capable of flexibly and rapidly adjusting their electricity demand. This particularly applies to industrial consumers, heat pumps, storage technologies and other controllable loads.

"At the low-voltage level, distribution system operators have the option under Section 14a of the EnWG to utilise consumer flexibility in order to avoid local overloads. This allows them to agree on grid-friendly control with end consumers who have controllable consumption devices such as heat pumps, electric vehicles and night storage heaters and, in return, charge a reduced grid fee."[111]

The “DENA Netzstudie III” clearly highlights that the curtailment of renewable energies is a particularly significant issue in regions high wind and solar power generation. The control zones most affected are those operated by 50Hertz and TenneT, which cover large parts of northern and eastern Germany as well as the coastal areas. These regions are characterized by substantial feed-in from onshore and offshore wind power but simultaneously face the challenge of limited grid capacity, which makes it difficult to transport the generated energy. This results in frequent grid bottlenecks and curtailments, where renewable electricity cannot be fed into the grid despite being generated.

4.1.2 Control Areas

In the 50Hertz control zone, the curtailment volume in 2023 for region D8N1—which includes Mecklenburg-Western Pomerania and offshore installations—amounted to 599 gigawatt hours (GWh). This represents a significant increase compared to 291 GWh in the previous year. Similarly high curtailment volumes were recorded in D8M2 (covering Saxony-Anhalt) and D8M4 (covering Northeast Brandenburg). At the same time, these regions reported a high number of curtailment hours, pointing to structural grid constraints.

A different situation is observed in the city of Hamburg, which historically shows no or negligible curtailment volumes, yet has still been designated as a relief region. The rationale behind this designation is that additional controllable loads in Hamburg could help alleviate grid congestion in downstream southern sections of the network.

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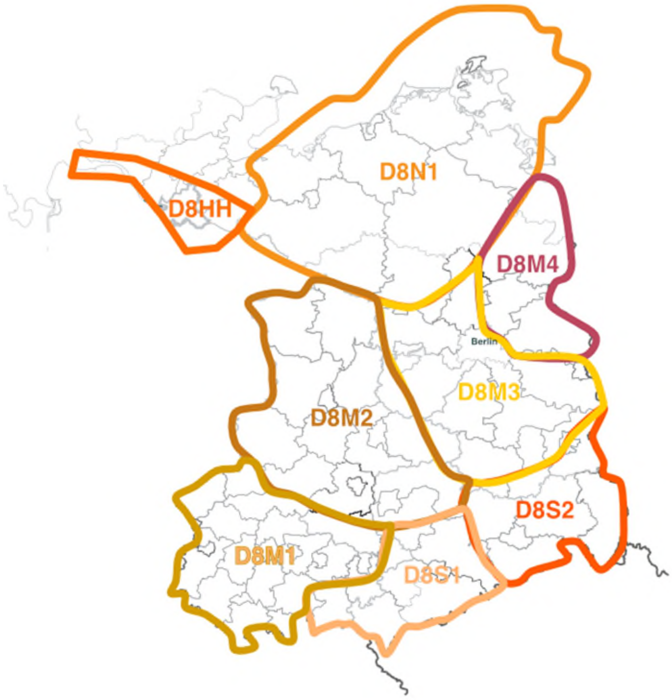
[111] Controllable consumption devices Monitoring report Federal Network Agency



REPRESENTATION OF THE DENA REGIONS OF THE 50HERTZ CONTROL AREA ©ÜNB-IMPLEMENTATION-CONCEPT-IN-ACCORDANCE-WITH-13K-ABS-6-

DENA region	EE-Curtailment Volume (GWh)	
	2022	2023
D8N1	291	599
D8M2	193	485
D8M4	386	265
D8M3	106	104
D8M1	45	67
D8S2	4	19
D8S1	3	4

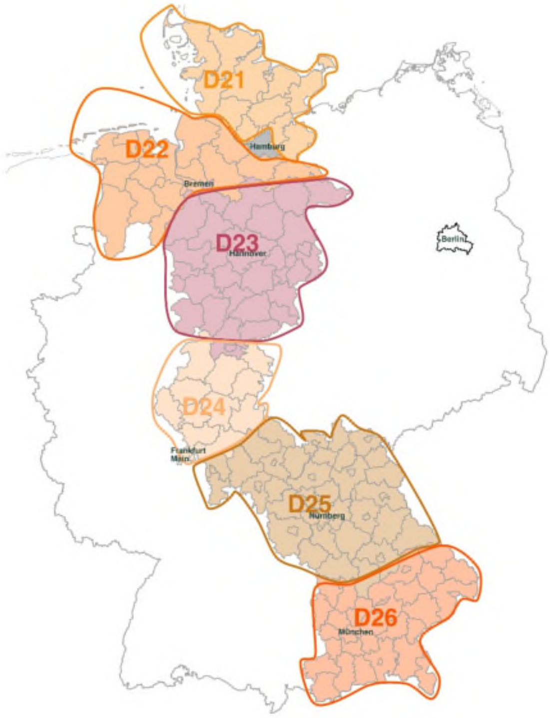
DENA region	EE-Curtailment Hours	
	2022	2023
D8N1	986	1.343
D8M2	1.327	1.289
D8M4	417	1.050
D8M3	605	483
D8M1	185	334
D8S2	17	71
D8S1	29	53

EE CURTAILMENT VOLUMES AND HOURS[112]

Also, in the TenneT control zone, which covers Northwest Germany, including Lower Saxony and parts of Schleswig-Holstein, significant curtailment volumes were recorded. In particular, the regions D22 and D21, which include large parts of Lower Saxony, Schleswig-Holstein, and offshore installations, were among the most affected, with curtailment volumes of 4,669 GWh and 3,951 GWh respectively in 2023. These areas not only report the highest volumes of curtailed energy, but also the longest curtailment durations, highlighting their critical role in grid relief strategies.

To address the issue of grid congestion, several relief regions were defined. For example, region T1 includes the Emsland and adjacent areas, while regions T5 and T6 cover parts of Schleswig-Holstein. These zones were delineated based on historical curtailment data and existing network constraints.

[112] Analysis in the 50 Hertz control area ÜNB implementation concept



MAP OF THE DENA REGIONS OF THE TENNET CONTROL AREA © IMPLEMENTATION CONCEPT IN ACCORDANCE WITH 13K ABS 6

DENA Region	EE- Curtailment Volume (GWh)	
	2022	2023
D21	839	3.951
D22	4.325	4.669
D23	493	982
D24	65	53
D25	0	1
D26	15	25

DENA Region	EE- Curtailment Hours	
	2022	2023
D21	1.783	3.176
D22	3.241	3.369
D23	612	992
D24	271	442
D25	0	5
D26	98	86

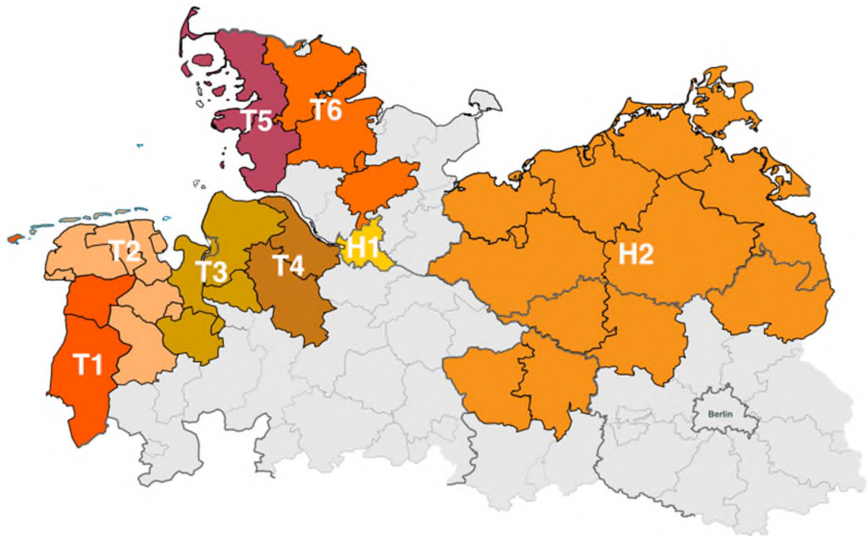
EE CURTAILMENT VOLUMES AND HOURS[113]

A particular situation can be observed in the Amprion and TransnetBW control zones, where curtailment volumes are comparatively lower. Within the 50Hertz control zone, specific relief regions have been designated to support grid stabilization. One example is relief region "H1", which includes the city of Hamburg. Historically, very little curtailment of renewable energy (RE) has occurred in this area, due to limited redispatch potential from renewables.

Nevertheless, additional flexible loads in this region can contribute to the reduction of grid congestion south of Hamburg. For this reason, Hamburg is classified as relief region H1. However, depending on the size and location of the flexible loads within the medium- and low-voltage grid, close coordination with the relevant distribution system operators (DSOs) and TenneT is required.

[113] Analysis in the TenneT control area TSO implementation plan

Looking forward, the potential designation of similar regions is under consideration, since the ongoing expansion of renewable energy capacity may require additional loads even in areas with historically low curtailment levels.



GEOGRAPHIC DEMARCATION RELIEF REGIONS

The geographical demarcation of the relief regions follows the provisions of § 13k of the German Energy Industry Act (EnWG), which obligates transmission system operators (TSOs) to clearly identify areas with high levels of curtailment and grid congestion. These relief regions are intended to enable targeted implementation of measures such as the integration of flexible loads or the activation of additional consumption capacity. The aim is to maximize the use of renewable energy while simultaneously reducing curtailment costs, which exceeded €800 million in 2021 and significantly contribute to rising grid fees for consumers.

The analysis of the dena Grid Study III and the designation of these relief regions clearly show that renewable curtailment is not a nationwide issue, but one that is concentrated in specific regions. It particularly affects wind-rich areas in northern and eastern Germany, where grid infrastructure has not kept pace with the rapid development of renewable energy. These clearly defined geographical relief regions provide a foundation for implementing targeted solutions that can reduce curtailments and improve renewable energy integration.

This includes technical innovations such as overhead line monitoring[114] and flexible AC transmission systems[115] (FACTS), as well as the use of flexible loads that adapt dynamically to grid requirements. The implementation of these measures should not only increase the efficiency of the energy system but also reduce the financial burden on consumers and promote acceptance of the energy transition.

Bitcoin mining offers a unique advantage in this context: facilities can be deployed decentrally and flexibly in the affected regions. For instance, mining units can be installed directly adjacent to wind or solar farms, thereby reducing the need for long-distance electricity transmission. This further relieves the grid and enables the direct use of locally generated renewable power.

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[114] Overhead line monitoring Tennet

[115] Flexible AC transmission systems Siemens Energy

4.1.3 Qualification Requirements for Participants

The implementation plan of the transmission system operators (TSO) under §13 EnWG explicitly defines the qualification criteria for participating entities.[116]). This requirement ensures that only technically suitable and reliable loads can participate in the system.

- To be eligible for the allocation procedure for curtailed electricity volumes under § 13k (2) sentence 2 and 3, and (6) EnWG, or the equivalent process for distribution system operators (DSOs) under § 13k (8) EnWG, a dispatchable load must meet specific conditions ensuring the additionality of electricity consumption. The load must be assigned to one of the segments defined in items 2, 3, or 4, and must meet both the segment-specific and general requirements listed in item 1. Among the general requirements is the need for technical controllability of the installation. This must be ensured either by the operator, the electricity supplier, or – if registration occurs via an aggregator – by the aggregator. In addition, the installation must not be part of a contractual agreement under § 13 (6a) EnWG between the TSO and the operator of a CHP plant. If the plant can replace fossil fuel-based heat generation with electricity-based heat generation (segment 1: "Substitution of fossil fuel-based heat generation"), additional special requirements apply.

According to the Federal Network Agency's (BNetzA) [117] definition of Segment 1:

"Segment 1 includes both existing and new facilities. It comprises dispatchable loads that are technically capable of replacing fossil-based heat generation with electricity-based heat generation during operation. This includes both full replacement and partial throttling of fossil systems. Electric heating units must be capable of technically substituting the fossil component."

"Applicable technologies include, for example, electric immersion heaters installed alongside CHP plants, which can fully or partially replace fossil-based heating. This also includes electric heating systems subsidized under § 7b KWKG, those formerly bound by § 13 (6a) EnWG agreements, or heating rods installed in water storage systems in residential or commercial settings. Other examples include bivalent glass furnaces, drying systems, steam generators, or food industry systems like gas-powered commercial ovens that can be switched to electric operation."

In view of the author, Bitcoin mining facilities meet the criteria of Section 13k (6) sentence 2 no. 3 EnWG for registration as a relief facilitiy, as they inherently comply with the statutory requirements for the use of curtailed electricity. The Federal Network Agency's criteria, based on the Power-to-Heat (PtH) method[118] , are also fully applicable. The law also sets out specific requirements to make sure that participating plants help reduce grid load, using excess electricity efficiently, and meet regulatory and technical standards.

A central requirement is that curtailed electricity volumes must be accounted for exclusively via a dedicated metering point, which does not supply any other consumer installations or electricity storage systems.

Bitcoin mining installations are inherently designed to measure and document their electricity consumption entirely and transparently through a dedicated market location.

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[116] Determination procedure for criteria regarding the additionality of electricity consumption Federal Network Agency

[117] Federal Network Agency Determination criteria Determination criteria

[118] PowerBDEW Federal Association of the Energy and Water Industry-to-Heat

Bitcoin mining facilities are inherently designed to document their electricity consumption entirely and transparently through a dedicatedarket location[119] .

This setup fully satisfies the requirement that electricity usage must be monitored with quarter-hour granularity. Mining facilities typically possess the necessary technology to meet this requirement through load profile metering or interval meter readings, in accordance with the technical connection conditions (TAB) of the respective grid operators. This ensures that the electricity consumed can be clearly accounted for and assigned to the § 13k instrument.

In addition, the legal text allows transmission system operators (TSOs) to define minimum power thresholds for qualifying relief facilities. For example, according to provision no. 4, electrolysers and heat pumps are only included from an installed electrical capacity of at least 100 kW.

Bitcoin mining systems are highly scalable and flexible in terms of capacity, enabling them to meet such specific requirements without difficulty. This applies both to individual installations and to the aggregation of multiple mining units within a relief group. Thanks to their modular design, mining operations can be implemented at both small and large scales, making them particularly well-suited for integration within the § 13k framework.

In addition, the legislation stipulates that transmission system operators (TSOs) may define a minimum capacity threshold for relief facilities. According to Clause 4, for example, electrolyzers and heat pumps are only considered if they have a minimum installed electrical capacity of 100 kW.

Bitcoin mining systems are highly scalable and flexible in their configuration, enabling them to easily meet such specific requirements. This applies both to individual units and to the aggregation of multiple mining devices within a relief group. Thanks to their modular design, mining systems can be operated across a wide range of capacities, from small-scale installations to large industrial applications, making them particularly well-suited for participation in the § 13k framework.

Another key element of the process is the prequalification of relief installations. As part of this verification, operators of relief facilities must demonstrate that they fulfill the technical requirements for data provision and communication with the transmission system operators (TSOs). This capability includes the transmission of consumption data, planning data, and information on non-availability, as required by the System Operation Regulation (SO Regulation).

Mining facilities are capable of continuously supplying this data, which facilitates their integration into the TSOs' monitoring and control systems. In addition, these facilities meet the requirement of operating exclusively as flexible, non-load-profile-dependent consumers. This refers to the ability to dynamically adjust electricity consumption based on current grid conditions. Bitcoin mining systems can be ramped up or down on short notice, without long-term impairment of operations.

This flexibility is a critical prerequisite for participating in the § 13k instrument, as it ensures that facilities can absorb excess electricity when available and reduce consumption when the grid requires relief.

In summary, Bitcoin mining installations fulfill the requirements of § 13k (6) Sentence 2 No. 3 EnWG through their technical flexibility, transparency, and scalability. They can efficiently utilize surplus electricity, document consumption transparently in quarter-hour intervals, and

[119] Market location Federal Network Agency

comply with the technical and regulatory framework. This makes them ideally suited to be registered as relief facilities and to contribute to the reduction of renewable energy curtailments and the relief of power grids under the § 13k mechanism.

4.1.4 Energy Efficiency and Additional Benefits

The BMWK input paper [120] places a particular emphasis on the energy efficiency of plants participating in surplus energy auctions: *"For other loads, additional electricity consumption is unlikely or cannot be sufficiently guaranteed, meaning that the disadvantages would outweigh the advantages. Participation in the instrument therefore exclusively covers heat loads and electrolysers."*

Heat is essential for numerous applications – from home heating to water heating and important industrial processes. With the continued growth of urban areas, district heating systems are increasingly seen as an effective solution to meet heating demand. However, these systems have traditionally relied on carbon-emitting fuels, resulting in environmental challenges.

One possible alternative is the use of waste heat from data centres. However, conventional data centres often face challenges when integrating into district heating systems, as the heat generated is often of low quality and the facilities are usually located far from the heat distribution infrastructure. This results in inefficient heat transport, energy losses and limited reusability.

In contrast, digital assets data centers - such as those used for Bitcoin mining - offer a promising solution. These centers convert electricity into heat efficiently and can be located on-site or near district heating facilities. This eliminates the need for extensive piping infrastructure and significantly reduces heat losses. Their proximity allows cost-effective, rapid deployment and an energy- and heat- efficient operation.

The integration of digital asset data centres into district heating systems brings numerous advantages including reduced emissions, significant cost savings and minimisation of waste heat. This combination ultimately supports the sustainability of both the district heating sector and the digital infrastructure.

The reuse of waste heat from Bitcoin mining maximizes the efficiency of the electricity used, as it is utilized not only for mining purposes but also for heat generation. The reuse of mining waste heat provides a valuable complement to the BMWK's June 27, 2023, concept of auctioning surplus electricity, enabling the concept's efficiency and sustainability objectives to be met more comprehensively. The paper envisions that surplus electricity from renewable sources should not only be used efficiently but also integrated with additional value-added aspects, such as heat reuse, to reduce curtailment costs and increase energy efficiency. Mining facilities that make productive use of waste heat offer considerable potential, as they contribute both to utilizing surplus electricity and to heat supply across various sectors.

During operation, Bitcoin mining facilities generate substantial amounts of heat, as the energy used for computational processes is released as thermal energy. This heat—often unused—can be integrated into various applications, creating additional utility. For example, mining facilities could be connected to district heating systems, using the waste heat to warm residential or commercial areas. This would be particularly efficient in urban regions or near existing heating

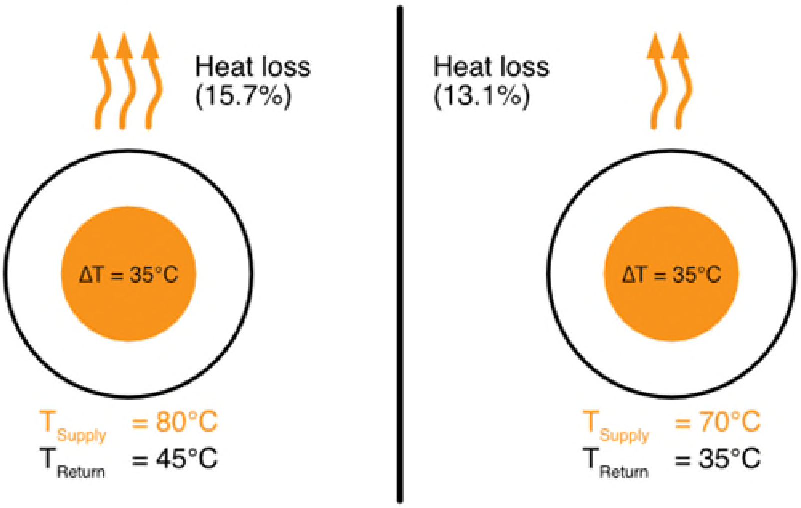
[120] BMWK A preventive benefit-instead-of-curtailment instrument for heat loads and electrolysers

networks, where waste heat utilization can replace fossil energy sources traditionally used for heating.

In addition, the waste heat from mining offers potential for industrial processes, especially those requiring low-temperature heat. Many industrial applications—such as drying or preheating materials—could benefit from the heat generated by mining. This would enhance industrial energy efficiency and improve the carbon footprint of such processes. Similarly, heating residential buildings - especially in areas where mining facilities are located close to heat consumers—is another application, minimizing heat losses due to long transport distances.

4.1.5 Differences from Conventional Data Centres

The integration of conventional data centres into district heating systems is difficult due to several factors. A key problem is the low temperature of the waste heat. Air-cooled data centres typically produce heat at temperatures of only around 25–35 °C[121] , while district heating networks[122] typically require heat of 70/35 °C to 80/45 °C or higher.



EXAMPLE OF HEAT LOSSES IN A DISTRICT HEATING NETWORK AT DESIGN TEMPERATURES (80/45 °C, LEFT) AND REDUCED SYSTEM TEMPERATURES (70/35 °C, RIGHT) – FRAUNHOFER INSTITUTE[58]

To close this temperature gap, additional heat generators such as electric boilers or heat pumps are required.

[121] TÜV Nord Making proper use of waste heat in data centres

[122] Fraunhofer Institute Low-Temperature District Heating Implementation Guidebook. Final Report

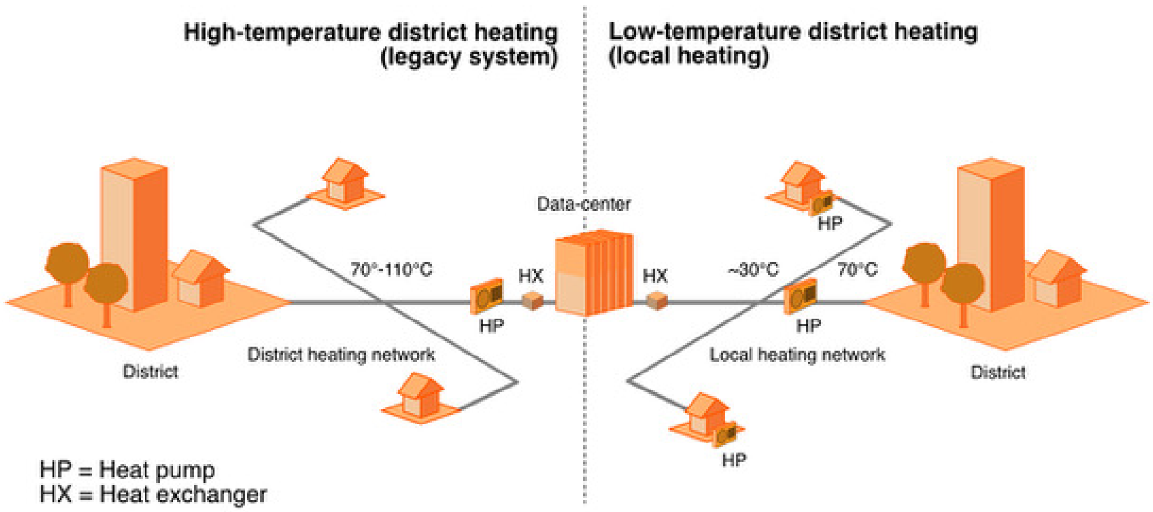


Figure 9 JLL Research Data centres in Germany[123]

However, this not only increases system complexity, but also raises costs - especially in the context of high liquidity prices. The low-grade heat output of traditional data centers is therefore considered a key reason why investments in heat recovery have so far remained limited.[124]

These combined challenges make the integration of conventional data centres into district heating networks inefficient and costly. As a result, there is a clear need for scalable, cost-effective and more compact solutions that can efficiently convert clean energy into heat and integrate more easily into existing district heating infrastructure. One promising solution is the use of Digital Asset Compute (DAC).

Digital Asset Compute (DAC) offers an efficient and sustainable solution for district heating by converting computational power used to generate digital assets like Bitcoin into substantial heat output. Unlike traditional data centres, which are often inefficient and geographically dispersed, DAC systems can convert up to 95% of electricity into heat, delivering it at temperatures of 55–75°C directly on-site. This reduces the need for additional heating systems, lowers costs and increases efficiency.

DAC data centres are compact, modular and scalable. A 2-megawatt DAC system[125] can be installed in a small space and supply district heating for up to 4,000 households. Thanks to their local integration, heat losses and transport costs are minimised. In addition, DAC systems contribute significantly to emission reduction: one-megawatt of DAC capacity can save up to 1,500 tonnes of CO_2 per year, assuming the system is powered by renewable energy. With their blend of efficiency, cost-effectiveness and sustainability, DAC systems are well-suited for modern district heating applications.

To test the hypothesis that Digital Asset Computing and district heating can successfully complement one another, Marathon launched a pilot project in Finland. In the Satakunta region, a 2-megawatt digital asset data centre was set to heat a community of 11,000

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[123] JLL Global Market Overview Germany 2024

[124] Borderstep Institute Economic efficiency of waste heat utilisation from data centres in Germany

[125] MARA Holdings Heating with Hashes

residents. The system was fully housed within a compact 50 x 50 ft space inside the local district heating facility.

4.1.6 Financial Compensation under Section 14 of the German Energy Industry Act (EnWG)

The financial compensation paid by the Transmission System Operator (TSO) to the participant is based on a difference in price remuneration. This is calculated as the difference between the so-called 13k price and the reference price.

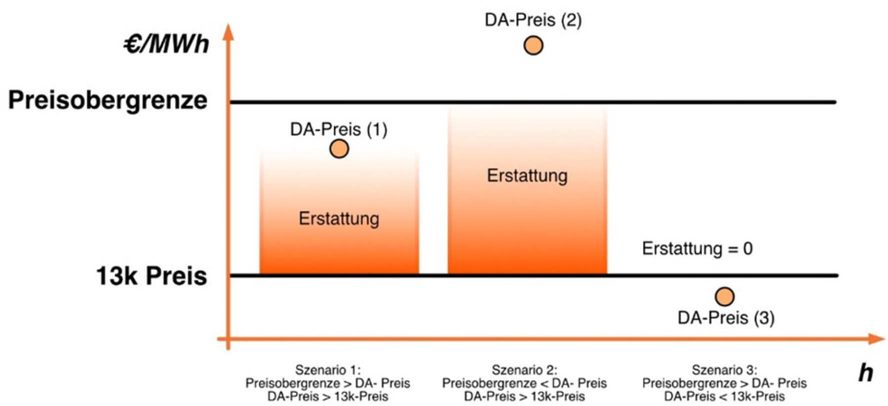
The reference price corresponds either to the day-ahead auction price on the electricity exchange as defined in §3 No. 42a EEG or to the price cap introduced in connection with §13k EnWG. This price cap is designed to limit financial risks for both the TSO and the participant, especially in extreme scenarios where day-ahead prices reach unusually high levels. It acts as a maximum reference price and therefore caps the compensation amount at this upper threshold.

The price cap is determined based on the maximum specific costs of Germany´s domestic grid reserve for the most recently completed calendar year with full data availability. As of now, this value is approximately €500/MWh.

While the 13k price and the price cap remain unchanged for defined periods, the reference price varies hourly in line with the day-ahead market price - provided it does not exceed the price cap. However, if the reference price falls below the 13k price, the compensation is capped at €0/MWh.

The activation of dynamic loads under this framework is significantly more cost-efficient than traditional curtailment compensation payments. While those compensations are based on the statutory feed-in tariffs, surplus electricity can be flexibly offered at lower prices, providing both economic and operational advantages[126] .

Financial reimbursement = MAX (reference price – 13k price; 0)
with reference price = MIN (DAPrice; Price Cap)



GRAPHICAL REPRESENTATION OF THE POSSIBLE SCENARIOS FOR FINANCIAL COMPENSATION TO BE PAID BY THE TSOS TO PARTICIPANTS[62]

[126] Determination of the 13k price ÜNB implementation concept p. 30

During the trial phase, the 13k price will be set uniformly for all participants, relief plants and relief regions. The objective is to define a reference price based on the lowest-cost technology to enable participation across all relevant technologies covered under §13 EnWG.

The 13k price is conceptually derived from production costs of a fossil fuel-based heat generation technology that relief plants are intends to replace. According to the Transmission System Operators (TSOs), natural gas price represents the central benchmark in this context, as they significantly impact both the operation costs and investment decisions for relief plants.

Power-to-heat (PtH) plants and electrode boilers are in direct competition with natural gas-based heat generation systems. In order to unlock the potential of these plants and ensure operational additionality, cost parity between electricity-based and gas-based technologies is essential. Electrolysers, which produce hydrogen using electricity, represent another major opportunity for relief installations, but they compete with alternative technologies such as natural gas reforming.

Since PtH plants represent currently the most cost-effective technology among the eligible participants, the 13k price is calculated based on the costs of fossil-based heat generation using gas boilers.

13-k-price	Reduction of EE-Curtailment		Macroeconomic Benefit		Reduction of Redispatch Costs	
< 0€/ MWh	strong incentive	++	potential loss of benefit (depending on magnitude)	o/-	potential cost increase (depending on magnitude)	o/-
= 0€/ MWH	incentive	+	increase	++	cost reduction	+
> 0€/ MWh	reduced incentive	+/o	increase (depending on magnitude)	+/o	significant cost reduction	++

IMPACT OF THE 13K PRICE ON TARGET ACHIEVEMENT[127]

Frontier Economics recommends setting the 13k price at a value greater than €0/MWh. The price level should be guided by the marginal participant who derives the least benefit from non-standard applications (NsA). Based on industry experience, an efficient natural gas heating system used by a commercial or industrial customer is considered a suitable reference value. These systems typically procure gas at wholesale-level prices, resulting in lower avoided fuel costs compared to small-scale consumers.

The avoided costs of such a gas heating system depend on various factors, all of which should be considered when determing the 13k price. Given the inherently rough estimates of the alternative costs for heat loads, the variability in actual procurement costs among consumers and temporal fluctuations in these costs over time, a safety margin (discount). To avoid jeopardizing the rollout of the §13k measure – especially in light of an expected oversupply—it is advised to apply a larger discount at the beginning. A discount in the range of 50% to one-third would result in a conservative initial value for the 13k price of approximately 30–40 €/MWh.Such a price discount would also ensure that new Power-to-Heat (PtH) plants built specifically with NsA could achieve reasonable margin. This would facilitate the amortizing of capital expenditures (CapEx) for new installations, such as immersion heater or Digital Compute Asset (DCA) systems.

[127] Frontier-Economic Impact of the 13k price on target achievement

4.1.7 Day-ahead price determination and 13k price using an example

The analysis of the monthly average spot prices in 2023 reveals shows significant fluctuations throughout the year. The highest monthly average price occurred in February 2023 at 12.83 ct/kWh, indicating increased energy demand in late winter and possibly tight market conditions. January 2023 followed with an average price of 11.78 ct/kWh. In contrast, the lowest average price was recorded in July 2023 at 7.76 ct/kWh, which is typical for the summer months, as lower demand and higher feed-in volumes from renewable energy sources, particularly solar.

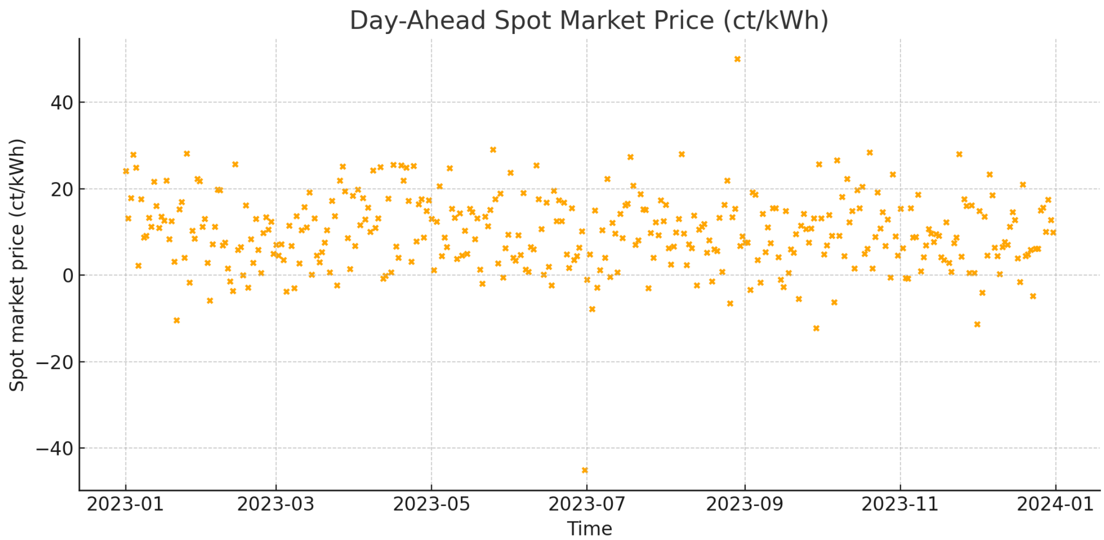
Overall, the trend in monthly averages reflects seasonal patterns and the dynamic nature of the electricity market.

The highest spot market price was 52.427 ct/kWh recorded on 11 September 2023 at 7 p.m. This spike likely resulted from exceptional market conditions, such as sudden demand peak or limited electricity supply. The highest daily average price was 20.273 ct/kWh on 23 January 2023, again pointing to unusual circumstances, such as high demand, low renewable output, or external factors.

On average across the year, electricity prices stood at 9.52 ct/kWh, indicating a moderate price level. However, this average mask significant monthly volatility. Particularly in the summer months - most notable July with 7.76 ct/kWh - an oversupply of renewable energy led to lower prices. Nevertheless, the occurrence of negative prices was less pronounced than expected.

In contrast, winter months like January (11.78 ct/kWh) and February (12.83 ct/kWh) showed substantially higher prices, underlining the challenges for market participants lacking flexible consumption models. However, price troughs during summer offer economic advantages for flexible consumers.

In summary, the data confirms that seasonal effects significantly influence electricity prices, and flexible load management offers clear strategic benefits.

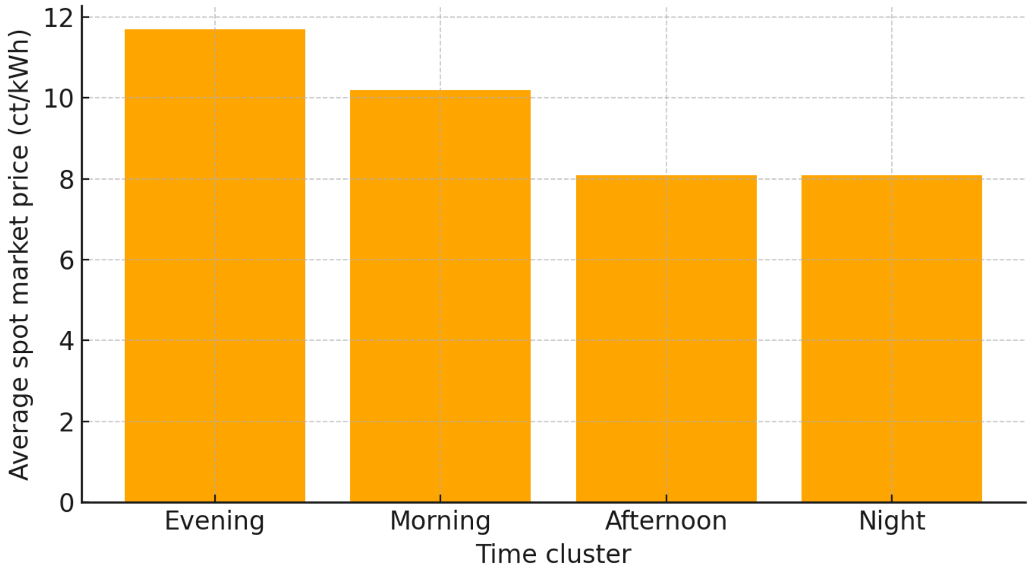


DAY-AHEAD SPOT MARKET PRICE (CT/KWH)[128]

[128] Epexspot

The temporal clustering of spot market prices in 2023 reveals distinct intraday patterns. The average price peaks in the evening, reaching approximates 11.66 ct/kWh, reflecting peak demand periods when households and industry energy demand increase. In the morning, the average price is also relatively high at around 10.19 ct/kWh, indicating rising activity at the start of the day.

In contrast, prices are significantly lower in the afternoon and during nighttime hours, averaging about 8.11 ct/kWh. These lower price levels may result from reduced demand or increased feed in form renewable sources, such as solar and wind power, especially during daylight hours.



AVERAGE SPOT MARKET PRICE BY TIME CLUSTER

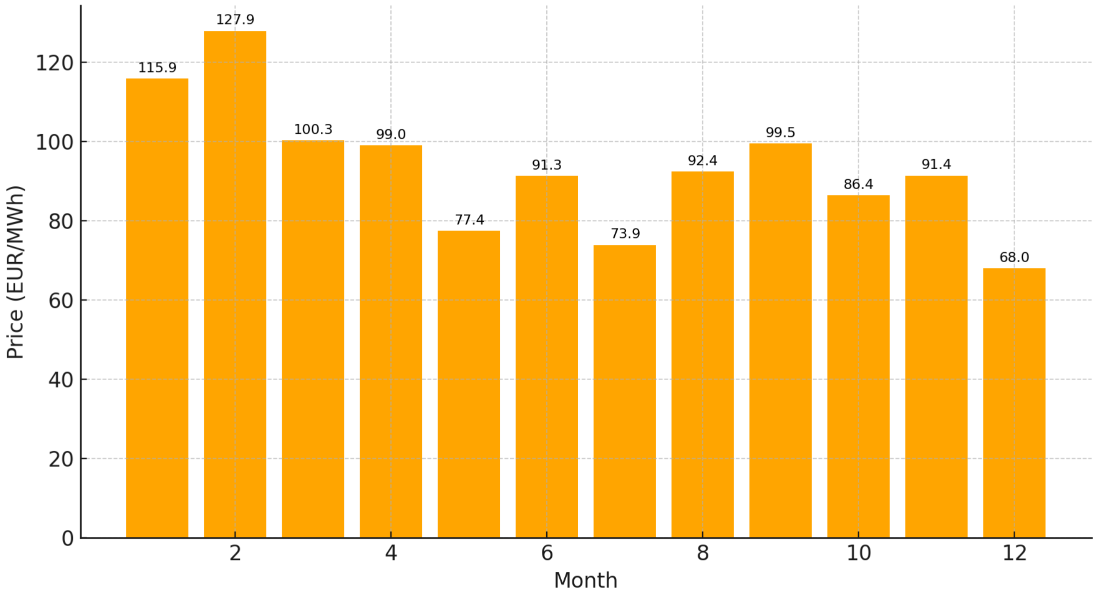
The price per MWh can be calculated based on the annual average price of 9.52 ct/kWh.

Since 1 MWh can be calculated based on the average annual electricity price of9,52 EUR/MWh. Since 1 MWh equals 1.000 kWh, the average price per kilowatt hour multiplied by 1.000:

Price per MWh = Average price per kWh × 1,000

This value provides a solid basis for sample calculations, especially when larger amounts of energy such as MWh are used as a unit. However, it should be noted that seasonal fluctuations or market conditions may influence the actual price.

4.1.8 Costs for control region D8N1 in grid congestion management with 13k



ENERGY-CHARTS.INFO; DATA SOURCE ETNSO-E, GRID TRANSPARENCY, EPEX SPOT; LAST UPDATE 25 NOVEMBER 2024, 04:20 CET

- **Distribution of curtailment volume:**
  The average curtailed power per hour is:

- Power per hour = $\frac{Gesamtleistung\ (MWh)}{Abregelungsstunden} = \frac{599\ (MWh)}{1343\ h}$

- **Monthly calculation:**
  For each month, the difference between the monthly exchange price of electricity and the 13k price is calculated, multiplied by the hourly output and the number of hours in the month.

- **Total costs:**
  Assuming that the curtailment volume of 599 GWh was distributed over 1343 hours, the monthly reimbursements based on the 2023 electricity exchange prices are as follows:

Month	Reimbursement (€)
January	3.787.177,50
February	4.388.673,33
March	3.010.973,33
April	2.945.582,50
May	1.867.382,50
June	2.560.225,83
July	1.691.176,67
August	2.615.633,33
September	2.969.043,33
October	2.313.637,50
November	2.565.716,67
December	1.397.167,50

The 599 GWh were distributed evenly over the 1,343 hours, resulting in a constant power output per hour. The monthly electricity prices minus the 13k price (€40/MWh) determine the reimbursement per MWh. These reimbursements were calculated according to the average hourly output and the number of hours per month.

The total financial reimbursement amounts to €29,112,390.00.

Explanation

The calculation of financial compensation is based on the difference between the 13k price and the reference price. Two key aspects are involved:

1. Reference price:

- Corresponds to the day-ahead price on the electricity exchange or a price cap set at a maximum of €500/MWh.
- The reference price can vary hourly, whereas the price cap remains constant.

2. 13k price:

- A uniform price defined during the pilot phase for all participants and regions.
- It is based on production costs, e.g. from power-to-heat plants, and is set to promote cost-efficient flexible of loads.

Financial reimbursement is calculated using the following formula:

Reimbursement = max (reference price−13k price, 0) where:

Reference price = min (day-ahead price, price cap)

Example calculation:

Given:

- 13k price: 40 €/MWh
- Price cap: 500 €/MWh
- Day-ahead price: 100 €/MWh
- Curtailed Load: 599 GWh (599,000 MWh)

Compensation per MWh:

Compensation per MWh = max (100 € − 40 €) = 60 €/MWh

Total compensation:

Total costs = 60 €/MWh × 599,000 MWh = 35.940.000 €

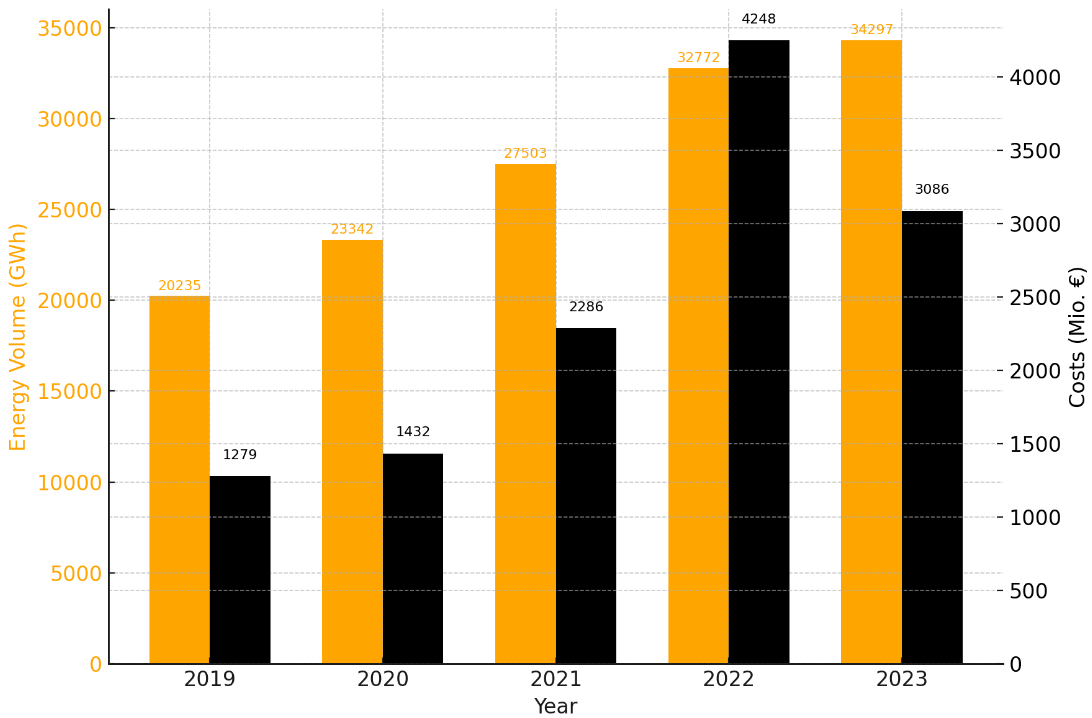
This results in a financial reimbursement of 60 €/MWh. For a curtailed load of 599 GWh, the total compensation amounts to 35.940.000 €, based on a 13k price of 40 €/MWh and a day-ahead price of 100 €/MWh, in accordance with the provisions of the remuneration.

4.1.9 Costs for Grid Congestion Management Measures in the German Power Grid until 2023

In 2023, grid congestion management measures in Germany resulted in costs amounting to €3.1 billion. Grid operators are legally obliged to implement measures that ensure the security and reliability of the electricity supply system.

One of the instruments used in congestion management is redispatch. This refers to interventions in the generation output of power plants to protect specific transmission line sections from overload.

The sharp increase in congestion management measures in 2022 was primarily due to rising fuel prices, which significantly impacted the cost of generation and the frequency of redispatch operations.



VOLUME OF GRID CONGESTION MANAGEMENT MEASURES AND COSTS[129]

"The feed-in from power plants on the market that was adjusted through redispatch amounted to around 27,133 GWh in 2023 (2022: 24,225 GWh). Of this, 10,478 GWh was attributable to redispatch with renewable energies (2022: 8,071 GWh). Although around 42 per cent of this amount related to renewable energy plants connected to the distribution grid, around 80 per cent of the grid congestion was caused by the transmission grid. Around 20 per cent of the redispatch volume involving renewable energies was triggered by congestion in the distribution grid."[65].

[129] SMARD Grid congestion management in 2023

4.2 Economic Efficiency, Integration, Heat Supply and CO_2

The TSO implementation concept places particular emphasis on the flexibility and controllability of the loads to respond quickly to surplus electricity. One of the key requirements is the ability to switch loads on or off within a short time, depending on the availability of electricity and the requirements. Bitcoin mining facilities are ideally suited in this respect. The Bitcoin mining process does not depend on a continuous power supply and can be paused or resumed as needed without compromising the functionality of the systems or processing workflows. This enables transmission system operators (TSOs) to manage mining operations precisely and dynamically in order to absorb excess electricity as soon as it becomes available. This flexibility makes Bitcoin mining an optimal solution for the requirements of §13k EnWG.

Another relevant aspect is the potential reduction in curtailment costs. Currently, curtailment of renewable energy plants incurs significant expenses, as operators of wind and solar plants must be compensated for lost feed-in revenues. These costs are ultimately passed on to consumers through grid fees. By utilizing surplus electricity for Bitcoin mining, these costs can be significantly reduced. Instead of paying expensive compensation, the excess electricity is used productively and transformed into economic value through the mining process.

As the DENA flagship study "Aufbruch Klimaneutralität" (The Road to Climate Neutrality)[130] shows, innovations are essential for achieving climate neutrality. Page 57 of the final report of the DENA flagship study emphasises that technological advances and the integration of new approaches are essential for an efficient and sustainable path to decarbonization. The DENA goes on to describe "active opportunity management and an innovation-friendly environment" as follows:

"An innovation-friendly environment is characterised by transparent communication, access to knowledge, a positive culture of error, openness to technology, freedom for ideas and the provision of the necessary resources (e.g. financial support or time). Meeting these criteria forms a good basis for the development of ideas. However, the idea itself does not constitute a successful innovation. Every idea then faces the challenge of implementation."

The author of this report identifies Bitcoin mining as a potential technology that could play a role in this context and therefore examines its characteristics and areas of application in more detail.

Mining can be described as an approach that, under certain conditions, can contribute to the flexibilisation and optimisation of electricity usage - particularly through the utilisation of surplus renewable energy. Such applications could not only help to ensure grid stability, but also incentives investments in renewable energy. By focusing on innovative technologies such as these, the transition to a climate-neutral energy system could be accelerated.

The following static calculation explores the economic incentives and application potential of Digital Compute Assets (DCA) systems based on simplified assumptions. The analysis adopts a pragmatic approach that illustrates the potential profitability and practical viability of such systems by considering specific factors such as energy consumption, efficiency and cost structure. The objective is to present the opportunities and challenges of this technology in the context of the broader discussion surrounding the deployment of DCA systems.

[130] DENA pilot study: The road to climate neutrality

4.2.1 Economic Efficiency

The following calculation[131] is intended to analyze the economic efficiency of a mining facility with a total output of 356kW. It considers the basic operating costs, revenues and potential challenges to provide a realistic picture of the financial sustainability of such a facility. Key factors such as electricity consumption, hashrate, Bitcoin price and network difficulty are incorporating the analysis to illustrate profitability under current market conditions. The aim is to establish a well-founded basis for assessing the economic benefits and risks associated with operating a mining facility.

Provisions

α^{BTC}	Block reward in BTC
λt	BTC-Bitcoin price in €
$\delta t^{(BTC)}$	BTC mining difficulty in TH/block
$\rho^{(CMD)}$	Hash power of a machine in TH/s
$PD^{(CMD)}$	Electrical power consumption of a machine in kW
$Pt^{(CMD)}$	Electrical work of a machine per day in kWh
N_{in}^{CMD}	Number of machines used in pieces
$PP^{(CMD)}$	Purchase price (net) of a machine in €
$\gamma^{(cooling)}$	Cooling factor of mining in %
MPF^{BTC}	Mining pool fee in %

Parameter values

Bitcoin-specific data (as of 19 December 2024):

$\alpha^{(BTC)}$	=	3.125 BTC without transaction fees
$\lambda\ t^{BTC}$	=	94,050 € / BTC
$\delta t^{(BTC)}$	=	108.52 Terra

CMD-specific data (Bitmain S21 pro):

$\rho^{(CMD)}$	=	234 TH/s
$PD^{(CMD)}$	=	3,564 kW
N_{in}^{CMD}	=	100
$PP^{(CMD)}$	=	4.644
UL_{year}^{CMD}	=	5 years

Other values:

$\gamma^{(cooling)}$	=	0.10
MPF^{BTC}	=	0.02
ir	=	0.05 (interest rate)

[131] Hedging Investments of Grid-Connected PV-BESS in Buildings Using Cryptocurrency Mining: A Case Study in Finland

Calculation of the profit factor ($\beta_t^{BTC,CMD}$)

$$\beta_t^{BTC,CMD} = \frac{3600 \, x \, \alpha^{BTC} \, x \, \rho^{CMD} \, x \, (1\text{-} \gamma^{cooling}) x \, \lambda_t^{BTC}}{2^{32} \, x \, \delta_t^{BTC} \, x \, P_D^{BTC}}$$

$$\beta_t^{BTC,CMD} = \frac{3600 \, x \, 3{,}125 \, x \, 234 \, x \, 0{,}9 \, x \, 94.050}{2^{32} \, x \, 108.52 \, x \, 3{,}564}$$

$$\beta_t^{BTC,CMD} = \frac{222827962500}{1661144229000} \approx 0.134$$

Calculation of hourly revenue (Rev_t^{BTC})

Rev_t^{BTC} $= (1\text{-}MPF^{BTC}) x \, \beta_t^{BTC,CMD} \, x \, P_t^{CMD}$

Rev_t^{BTC} $=(1\text{-}0{,}02) x \, 0{,}134 \, x \, (3{,}564 \, x \, 1)$

Rev_t^{BTC} $= 0{,}98 \, x \, 0{,}134 \, x \, 3{,}564 kW \approx 0.47$ € / h

Calculation for control region D8N1 with 1,343 control hours and a control capacity of 356 kW

N_{in}^{CMD} = 100 units

Rev_t^{BTC} $= (1\text{-}MPF^{BTC}) x \, \beta_t^{BTC,CMD} \, x \, (P_t^{CMD} \; x N_{in}^{CMD})$

Rev_t^{BTC} $= (1\text{-}0{,}02) x \, 0{,}134 \, x \, (3{,}564 kW \, x \, 1343 h \, x \, 100)$

Rev_t^{BTC} $= 0{,}98 \, x \, 0{,}134 \, x \, 478.108 \approx$ £56,785.14

4.2.2 Determination of Criteria regarding the Additionality of Electricity Consumption

The following outlines how, in accordance with ³13k(3) sentence 3 in conjunction with §13k(1) of the German Energy Industry Act (EnWG), the definition criteria [132] for the additionality of electricity consumption is used to ensure that the reduction in active power generation from renewable energy installations (§3(1)EEG) due to electricity-related grid congestion is minimized.

The aim is to ensure that only electricity consumption is incentivized that would not have occurred without the measure under §13k EnWG, thereby achieving real relief of grid bottlenecks. Simply shifting electricity procurement from existing consumers would not produce the desired effect and could instead increase grid charges through windfall effects (see BT-Drs. 20/9187, p. 147 f.).

Moreover, undesirable incentives such as so-called increase-decrease gaming must be avoided, as they could further aggravate grid congestion (BT-Drs. 20/9187, p. 147). The following explanation demonstrates how these objectives are intended to be achieved through the proposed measure.

[132] Procedure for determining the criteria regarding the additionality of electricity consumption that a switchable load must meet in accordance with Section 13k (3) sentence 3 of the Energy Industry Act (EnWG)

The mining process results in significant heat generation, as the computing hardware used converts most of the electrical energy into thermal heat. The devices used in mining, ASICs (Application-Specific Integrated Circuits), produce large amounts of waste heat due to their high computing power. Up to 95% of the energy consumed is converted into heat, making it a potentially valuable resource.

The temperature reaches in this process range between 55 °C and 75 °C, depending on the cooling technology used. These values are sufficient to feed the heat into district heating systems or to be used for space heating, hot water production or industrial processes. By using heat exchangers, this waste heat can be directly transferred to district heating networks, achieving a dual use of energy: The computing power supports grid congestion management, while the generated heat is reused in a meaningful way.

The integration of mining facilities into heat supply systems offers numerous advantages. The waste heat, which would otherwise remain unused, is efficiently utilised and contributes to energy savings. Furthermore, the use of renewable energy in mining operations, combined with the reutilization of waste heat, enables a reduction CO_2 emissions. Due to their modular architecture, mining systems can be flexibly scaled to match varying heat demands, allowing both small-scale and large-scale applications to be realised.

This utilization of heat from the mining process represents an innovative approach that promotes energy efficiency and sustainability, while simultaneously reducing operating costs and optimizing resource use. As a result, mining facilities can be considered not only as rule-based data centres, but also as valuable sources of heat.

a. Heat Dissipation

The heat capacity is calculated based on the electrical power (P) of the devices, assuming that approximately 95% of the electrical energy is converted into heat.

Formula:

$$Q = P \times t$$

- Q: Heat energy (in joules or kWh)
- P: Electrical power of the device (in kW)
- t: Operating time (in hours)

Heat capacity for the relief system

For *N* devices:

$$Q_{total} = N \times P \times t$$

Application of parameters:

- Number of devices (*N*): 100
- Power consumption per device (P): 3.564 kW
- Operating time (t): 1343 h / year

Calculation

$$Q_{(total)} = 100 \ x \ 3{,}564 kW \ x \ 1343 h/a$$

$$Q_{(total)} = 478.645 kWh/a$$

Conversion to joules

Heat energy in joules:

$Q_{(total)} = Q_{total}^{kWh}\ x\ 3{,}6\ x\ 10^{6}J$

$Q_{(total)} = 478.645 kWh/a\ x\ 3{,}6\ x\ 10^{6}J$

$Q_{(total)} = 1{,}723\ x\ 10^{12}J$

To efficiently integrate the waste heat from a mining facility into a heating system, it is crucial to match the heat generated to the typical requirements of applications such as space heating or hot water supply. The heat capacity of the system is considered to optimally utilize the available energy. The following section calculates how the generated thermal energy generated can be specifically applied for these purposes.

Assumptions for the heating system

- Heat energy of the system: Q_{total} = 478.645 kWh / year; $Q_{(total)} = 1{,}723\ x\ 10^{12}J$
- Efficiency of the heating system: 95% of the heat energy is converted into usable energy .
- Specific heat capacity of water (c): 4,186 kJ/(kg\K)
- Density of water (ρ): 1 kg/1l
- Heating temperature: We heat water from 10°C to 55°C

Calculation of heating capacity - energy required to heat water

The energy required to heat water is calculated as follows:

Q=m x c x ΔT

- Q: heat energy in joules
- m: mass of water in kilograms (equivalent to litres)
- c: Specific heat capacity of water (4,186 J/kg*K)
- ΔT: Temperature difference (55°C – 10°C = 45 Kelvin)
- To heat 1 litre by 45K

$Q = 4.186 \frac{J}{kg*K}\ x\ 1kg\ x\ 45K$

Q= $188{,}370kJ$ = 0.052kWh

Maximum amount of water that can be heated

The available heat energy is Q_{total} =478.645 kWh / year

With an efficiency of 95%, this results in:

$Q_{usable} = 478.465\ x\ 0{,}95$

$Q_{usable} = 454.712\ kWh$

The amount of water that this energy can heat:

$$m= \frac{Q_{nutzbar}}{0{,}052kWh}= \frac{454.712}{0{,}052} =8.744.461\frac{Liter}{Jahr} bei\ 45K\ Temperaturdifference$$

In conclusion, the use of waste heat from mining facilities for the "substitute fossil fuel-based heat generation"[133] is not only a technical possibility but also a promising approach to improving efficiency and sustainability. The calculations and concepts presented here demonstrate how this waste heat can be efficiently integrated into heating systems to support for example, space heating and domestic hot water production,

This clearly demonstrates that mining facilities can serve as valuable energy sources within local and regional heating networks far beyond their primary purpose or digital asset computation.

It is important to note that the use cases outlined are only a subset of potential applications. The author of this document emphasises that further working papers will explore additional applications in more detail.

4.2.3 Integration

The integration of Bitcoin mining into the framework of §13k EnWG offers significant potential to achieve both technical and economic objectives. In addition to efficiently utilizing surplus renewable energy, the targeted deployment of mining facilities in structurally weak regions opens new perspectives. Especially in rural relief areas with high feed from renewable sources but limited economic prospects, Bitcoin mining could act as catalyst. It presents a chance to generate new revenue streams, stimulate local infrastructure investment, and sustainably improve the economic attractiveness of these regions. Simultaneously, the use of surplus electricity contributes to stabilizing the energy and power grids and strengthens the interconnection between regional and national energy systems.

However, the associated challenges must not be overlooked. Bitcoin mining´s public image is often shaped by criticism of its energy consumption. Within the framework of §13k EnWG, transparent communication is essential to demonstrate that the electricity demand of these facilities is met through surplus renewable energy that would otherwise remain unused. Moreover, maintaining Germany´s long-term attractiveness as a location for mining operations requires a stable regulatory framework and economic incentives to prevent migration effects. The technical and organisational effort needed to integrate mining facilities into the transmission network also requires close collaboration between operators, Transmission System Providers (TSOs), Distribution System Operators (DSOs) and relevant authorities.

The flexibility and scalability of Bitcoin mining make it an ideal solution for the requirements of §13k EnWG. As dispatchable loads, mining facilities can not only contribute to reducing curtailments and improving the utilisation of renewable energies but also enhance grid stability and create economic benefits. If successfully implemented, Bitcoin mining could represent an innovative model linking the energy transition with modern technology, making it a key tool for the future of energy supply.

Furthermore, the measures of §13k EnWG are closely tied to corporate ESG (environmental, social, governance) reporting obligations. The targeted use of surplus renewable energy and

[133] Federal Network Agency Determination criteria

activation of flexible loads contribute not only to resource efficiency and cost reduction but also strengthen companies' sustainability strategy. Businesses implementing such measures can highlight them as part of their ESG strategy and thus improve their position in the assessment by investors and stakeholders. The integration of sustainable technologies into corporate governance thus offers not only environmental benefits but also a clear competitive advantage.

Overall, the integration of Bitcoin mining into the §13k EnWG concept illustrates how technological innovation, economic development and environmental sustainability can be successfully combined. This convergence not only offers solutions to the current challenges of the energy transition but also unlocks new strategic opportunities for corporates and regions that actively seek to contribute to the transformation of the energy and economic system.

About the authors

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LESolution

Lars Eichhorst is an expert in energy technology and regulatory frameworks under Germany's Energy Industry Act (EnWG), with a particular focus on the interface between renewable energy systems and blockchain-based load concepts. He is a certified master electrician, energy consultant, and founder of LESolution - the only officially registered craft enterprise in Germany specializing exclusively in the design and deployment of Bitcoin mining systems. He also serves as managing director of 21PV GmbH, a company that develops strategies to monetize surplus renewable electricity through flexible, grid-responsive loads.

Since 2024, Eichhorst has been a board member of the German Bitcoin Association (Bitcoin Bundesverband), where he contributes to regulatory discourse at the national level. His professional focus lies in the practical and regulatory implementation of §13k EnWG, aimed at enabling the efficient use of excess power—particularly from photovoltaic systems—through controllable loads such as Bitcoin mining.

Beyond his entrepreneurial and regulatory roles, Eichhorst is actively engaged in knowledge transfer. He regularly speaks at industry conferences, workshops, and professional training events, where he presents technical and economic insights on the integration of mining systems into renewable energy infrastructures. His platform *Ueberschussenergie.de* provides tools to evaluate the feasibility and profitability of such applications.

Through his work, Eichhorst advocates for a broader understanding of Bitcoin mining as more than an energy consumer—as a dynamic mechanism for grid stabilization, flexible sector coupling, and infrastructure support in decentralized energy systems.

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Treasury Managerin & Transformations-/ Breathwork Coach

With over a decade in corporate finance and treasury, Janine Paas brings extensive expertise in financial management, blockchain and Bitcoin technology, combining it with a holistic view of transformation and corporate sustainability.

Having held positions in international corporates and banking, she combines deep knowledge of Bitcoin, technological payment systems, and risk management and risk management – including liquidity control, market exposure, compliance regulatory and financing strategies. She represents a perspective in where economic activity, social responsibility and human development are understood as interconnected.

Through her professional experience and her freelance as a systemic transformation and breathwork coach, she combines technological expertise with a systemic understanding of personal development. This approach allows her to see Bitcoin not merely as a technological asset, but as a catalyst for a profound transformation in human interaction and entrepreneurial practice activity.

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Peter Rochel is Managing Partner of UTXO Solutions GmbH and serves as Chairman of the ESG & Education working groups at the Bitcoin Bundesverband (German Bitcoin Association). A pioneer in the jobs-to-be-done approach, he has supported over 700 transformation projects across the energy, industrial and digital sector since 2006. He co-developed the Wheel of

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His focus lies on Bitcoin-based sector coupling, grid flexibility and ESG/CSRD reporting – supporting companies from strategic design to KPI validation. With nearly two decades of experience in solar and energy technologies, including participation in the Barcelona Energy Forum 2007, he combines technical expertise with data-driven innovation methods to scale market-oriented applications of Bitcoin and enable profitable integration of renewable energy.

He is the creator of the JTBD Inoovation Framework and specializes in aligning innovation strategy with measurable ESG and business outcomes. He regularly shares insights through the podcasts "The Bitcoin Effect" and "Innovate + Upgrade" as well as through specialized white papers.

Acknowledgements

The compilation of the individual contributions was made possible by the kind support of Shkrep Haxhimusa. His commitment and assistance contributed significantly to the completion of this paper. We would like to express our sincere thanks for this.

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