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Modeling the Environmental and Regulatory Impacts of Cryptocurrency Mining: A System Dynamics Approach to Policy Evaluation

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ABSTRACT: This study examines the multifaceted challenges posed by Bitcoin's rapid growth, focusing on economic, social, and regulatory issues, including illegal mining, high energy consumption, security vulnerabilities, and tax evasion. Through a System Dynamics (SD) modeling approach, the research explores the feedback loops and interactions within the cryptocurrency ecosystem. Key findings emphasize that strategic regulatory interventions are vital for balancing innovation with sustainability, mitigating environmental impacts, and ensuring power grid stability. The study underscores the role of evidence-based policymaking (EBPM) in formulating data-driven policies for the cryptocurrency sector. By integrating EBPM with SD modeling, the research provides actionable insights for policymakers to understand the broader implications of mining efficiency, network difficulty, and supply growth within the Bitcoin ecosystem. Four distinct scenarios were modeled to analyze varying outcomes influenced by technological advancements and miner participation. Scenario 1 depicts stable growth achieved through gradual increases in mining difficulty, resulting in limited yet sustainable expansion. Scenario 2 highlights the advantages of rapid technological adoption, driving short-term growth while raising concerns over energy consumption and market saturation. Scenario 3 focuses on long-term stability with a balanced growth strategy, ensuring sustainability but at the cost of slower expansion. Scenario 4 illustrates how rapid technological advancements can lead to increased mining activity, though accompanied by resource strain and diminishing returns. These findings stress the importance of adopting a balanced approach to managing Bitcoin mining. Policymakers, miners, and investors must align technological growth with sustainability to maintain the Bitcoin network's long-term stability and profitability. Establishing a unified policymaking framework is critical for effective governance and coordination among stakeholders, including the Central Bank, Ministry of Energy, and Ministry of Industry. Additionally, public education campaigns on digital currencies and blockchain technology are imperative for fostering informed participation and mitigating misuse.

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1- Introduction

Blockchain technology has emerged as a transformative innovation, particularly within the realm of cryptocurrencies, over recent years. Its decentralized nature enables secure, transparent, and immutable transactions, leading to rapid adoption across industries, with Bitcoin standing out as a prominent digital currency. This growth is driven by factors such as lucrative investment opportunities, ease of mining and trading, and the involvement of both retail and institutional investors [1]. However, this expansion has also introduced significant challenges, particularly in environmental sustainability and regulatory compliance.

Cryptocurrency mining, especially Bitcoin, demands vast computational power, resulting in high energy consumption. Research by Khezr et al. (2019) and Guo et al. (2022) highlights the considerable environmental toll of cryptocurrency mining, including excessive energy usage and carbon emissions [2]. These environmental concerns are further complicated by regulatory challenges, as cryptocurrencies often operate within legal grey areas. For instance, countries like China and the United States face difficulties in balancing the economic advantages of cryptocurrencies with risks like money laundering and tax evasion [3].

The UK Cabinet Office categorizes evidence types into systematic research, case studies, statistical data, economic documents, ethical considerations, expert opinions, and internet-based evidence [4]. Key strategies to optimize evidence use in policymaking include:

- Aligning research strategies across institutions.
- Improving access to research data.
- Sharing research goals and outcomes across sectors.

To address these challenges, this study employs an

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Evidence-Based Policymaking (EBPM) approach integrated with System Dynamics (SD) modeling. EBPM emerged as a response to the limitations of opinion-based approaches, emphasizing decisions grounded in robust empirical research to mitigate biases and untested assumptions. Initially inspired by evidence-based medicine, this framework applies empirical data to diagnose and address policy issues, akin to diagnosing and treating diseases. By ensuring that policies are based on solid evidence rather than intuition, EBPM strengthens the reliability and effectiveness of policy recommendations. System Dynamics, in turn, has become a key component in this paradigm, providing structured methods for modeling and simulating policy outcomes. This approach allows policymakers to simulate complex systems and predict the impacts of different interventions, particularly in the context of Bitcoin mining.

System dynamics modeling has proven instrumental in understanding the intricate interactions within the cryptocurrency ecosystem. By focusing on feedback loops, time delays, and non-linear interactions, this approach enables a structured analysis of interdependent factors such as energy consumption, regulatory frameworks, and market demand. By simulating scenarios, policymakers can forecast long-term impacts and design strategies to mitigate environmental harm while fostering blockchain innovation [5]. In fact, previous studies have applied system dynamics (SD) to understand various dimensions of cryptocurrency and Bitcoin mining.

The UK pioneered EBPM in public administration, starting with Tony Blair's government in 1997. Since then, this approach has gained international traction, with increasing reliance on quantitative models and analytical tools to shape policy decisions. Countries such as the United States, Scandinavian nations, and Australia have institutionalized this approach, leveraging System Dynamics to address complex policy issues and improve outcomes. The UK Cabinet Office categorizes types of evidence used in policymaking into systematic research, case studies, statistical data, and expert opinions. Key strategies to optimize the use of evidence in policymaking include improving access to research data and aligning research goals across sectors.

In the broader field of economic modeling, Clò and Fumagalli (2019) employed a Difference-in-Differences approach to analyze the effects of price regulation on energy imbalances. Although their study focused on energy markets, the methodology they used provides valuable insights into how regulatory interventions can impact sectoral dynamics. By simulating the long-term effects of price regulation on energy systems, their work underscores the utility of modeling techniques, such as system dynamics (SD), in capturing the complex interactions between regulation, profitability, and sustainability. This approach is particularly relevant for studying the Bitcoin mining sector, where energy consumption and environmental sustainability are central concerns[6].

Similarly, Roozkhosh and Pooya (2024) conducted a dynamic analysis of Bitcoin price behavior under the influence of market news, sentiments, and government support policies. Their study demonstrated how system dynamics can model the interplay between external factors and Bitcoin price fluctuations, providing insights for policy design and market forecasting [7].

Another relevant contribution comes from Omole (2023), who used system dynamics (SD) to explore Bitcoin market dynamics. His study demonstrated how SD could be employed to simulate the effects of various factors on the market's stability, highlighting its potential to inform policymaking in the rapidly evolving cryptocurrency sector[8].

The evaluation of blockchain policies has gained prominence due to its far-reaching implications for financial markets, governance, and regulatory systems. Research such as that by Hinsdale et al. (2022) demonstrates blockchain's potential to enhance transparency and reduce corruption, particularly in nations with underdeveloped financial systems [9]. Such findings underscore the transformative power of blockchain in combating fraud and fostering accountability in global ecosystems. The regulatory challenges surrounding cryptocurrencies, however, remain a central concern. Scholars highlight the tension between enabling innovation and enforcing regulations, especially in financial markets reliant on blockchain technologies for decentralized finance (DeFi) and cross-border transactions. Swan et al. (2015) emphasize the need for robust frameworks to capitalize on blockchain's benefits while ensuring market integrity [10]. Liu et al. (2023) further explore blockchain's role in enhancing financial stability through improved security and oversight in policy enforcement [11].

System dynamics studies have consistently shown the effectiveness of this approach in evaluating complex systems under varying regulatory scenarios. By analyzing feedback loops and time delays, this method helps identify unintended policy consequences and predict long-term outcomes. Researchers have applied system dynamics to fields such as environmental policy, public health, and economic stability, making it particularly suited for studying the cryptocurrency ecosystem [12, 13].

This study introduces several innovative aspects that address key gaps in the existing literature on Bitcoin mining and its challenges. First, it integrates environmental and regulatory dimensions, providing a unified system dynamics framework to analyze their interplay within the Bitcoin mining ecosystem. This dual-focus perspective addresses a gap in prior studies that typically examine these aspects in isolation. Second, the study applies system dynamics modeling to Bitcoin mining, employing causal loop diagrams and stock-and-flow models to capture complex interactions, feedback loops, and non-linearities unique to cryptocurrency ecosystems. Third, it conducts a policy trade-off analysis by incorporating real-world data, enabling the evaluation of energy policies and regulatory interventions. This approach provides policymakers with predictive tools to assess the long-term impacts of various strategies, filling a key gap in existing research. Fourth, the model includes speculative market dynamics, exploring how investor sentiment and market volatility influence mining activity and energy consumption, thereby expanding the scope beyond traditional economic or environmental factors. Finally, the findings offer practical recommendations for policymaking, addressing challenges such as energy grid stability, tax evasion, and mining profitability, with tailored solutions to meet the needs of regulators and stakeholders.

By utilizing system dynamics to evaluate the environmental and regulatory challenges of Bitcoin mining, the research incorporates quantitative and qualitative data to model interactions among factors such as economic incentives, regulatory frameworks, energy consumption, and market behaviors. Building on prior studies, it offers a holistic perspective and real-world insights into policy trade-offs, aiming to bridge gaps in the literature by integrating environmental, economic, and speculative dimensions and providing actionable recommendations for the cryptocurrency mining sector.

This paper is structured into several key sections. Following the introduction, which outlines the significance of the topic and the objectives of the study, Section 2 presents the methodology, detailing the approaches used for data analysis and model simulation. In Section 3, the System Dynamics model is described in detail, explaining the various steps taken in the model development process, including the identification of variables and actors, feedback analysis, and different simulations. Section 4 discusses the simulation results and policy analysis, highlighting how different policy changes and regulatory interventions can impact the Bitcoin mining ecosystem. Finally, Section 5 concludes the paper and offers recommendations for future research.

2- Methodology

This study integrates evidence-based policy-making (EBPM) with System Dynamics (SD) to address the challenges within cryptocurrency and blockchain ecosystems, particularly Bitcoin mining[14]. EBPM ensures policies are based on empirical data rather than anecdotal information, enabling accurate, data-driven decision-making[15]. This combined framework offers a detailed analysis of market behaviors and the Bitcoin mining network.

Modeling Process: The study begins with a comprehensive review of the Bitcoin mining ecosystem to identify critical challenges and variables, such as mining profitability, energy consumption, regulatory policies, and key stakeholders, including miners and regulators. Expert feedback from cryptocurrency, energy, and economics specialists refines the model for real-world applicability. The process includes the creation of causal loop and stock-and-flow diagrams, which illustrate the relationships and dynamics among variables.

Simulation and Validation: Quantification defines mathematical relationships between variables, enabling the simulation of policy scenarios using real-world data. Simulations explore potential trends, while sensitivity analysis and scenario testing ensure model reliability and predictive accuracy. This structured methodology leverages EBPM at every stage, ensuring realistic, actionable insights for policymakers. SD modeling evaluates existing policies and develops evidence-based recommendations for the Bitcoin mining ecosystem.

2- 1- Evidence-Based Policy Making

EBPM addresses complex issues in Bitcoin mining by relying on systematic research and empirical data, reducing biases and enhancing policy reliability[16]. It is applied here to tackle challenges such as environmental sustainability, energy use, and regulatory compliance, ensuring policies mitigate impacts while fostering innovation[17].

By integrating SD, EBPM strengthens policy modeling by simulating interactions among factors like energy consumption, regulatory frameworks, and market demand[4]. For example, EBPM-SD simulations can evaluate energy policies such as carbon taxes or incentives for renewable energy use, providing insights into balancing growth with sustainability.

Globally, EBPM and SD are institutionalized in policymaking, as seen in the U.S., U.K., and Australia, proving effective in cryptocurrency regulation. In this study, EBPM ensures that policy recommendations are rooted in real-world data, allowing for a comprehensive assessment of long-term policy impacts[18].

This approach ensures policies for Bitcoin mining are effective, adaptable, and sustainable, addressing energy, market, and environmental concerns in a rapidly evolving ecosystem.

2- 2- Conceptual Framework for Policy Making

A strategic roadmap for cryptocurrency policy-making can address the challenges and opportunities identified earlier. Table 1 presents a conceptual framework for cryptocurrency policy, as proposed by [14][1]. This framework organizes policy concerns into actionable domains, including economic, regulatory, and social dimensions, and identifies responsible institutions for their implementation.

The cryptocurrency ecosystem faces numerous interconnected challenges, including macroeconomic threats, social crimes, fraud, investment security issues, and knowledge gaps, which highlight its complexity. To address these, an initial model was constructed using a Causal Loop Diagram (CLD) approach, based on hypotheses. This model was refined through expert interviews, ensuring its alignment with real-world conditions and enhancing accuracy by capturing nuanced relationships and feedback loops.

Key dynamics include the positive relationship between the number of miners and mining volume, which boosts system output, and the balancing negative feedback loop between miner numbers and initial mining costs, helping stabilize excessive activities. The model integrates causal loops and stock-and-flow diagrams to represent the ecosystem comprehensively across social, technical, economic, and governance dimensions. Variables are progressively added to balance complexity and clarity. The research problem

1 Islamic Parliament Research Center. (2018). *Cryptocurrency Mining and the Regulatory Role of the Islamic Consultative Assembly*. Available at: https://rc.majlis.ir/fa/report/show/1225846

Table 1. Conceptual Framework for Cryptocurrency Policy-Cryptocurrency Mining and the Regulatory Role of the Islamic Consultative Assembly1.

		responsible institution	**Central Bank**	**Ministry of Economy**	**Central Bank**	**Stock Exchange Organization**	**responsible institution**		
		challenge	real economy threat	equipping and allocating resources	monetary policies	investment risk	Challenge		
responsible institution	challenge	axis	threat of macroeconomics				axis	challenge	**responsible institution**
tax affairs organization	tax evasion	laying the foundation for violations and Social crimes	the conceptual framework of cryptocurrency policy				theoretical and scientific problems	jurisprudence	Jurisprudence Committee of the Central Bank and Stock Exchange Organization
Supreme Council for Combating Money Laundering	money laundering							nature	Scientific and university centers
FATA police, Supreme Council of Cyber Space	cyber crimes							people's ignorance	Media and educational institutions
Ministry of Information	financing of terrorist groups							mechanism of legal action	Judiciary
Responsible institution	challenge	axis	problems of people's capital security				axis	challenge	**Responsible institution**
		Challenge	Inheritance of infringing exchanges	Inheritance	Hacking	Lost	Challenge		
		Responsible institution	Central Bank	the person himself	FATA police	the person himself	**Responsible institution**		

was systematically analyzed, identifying relevant policies and challenges before modeling. This approach ensures an accurate representation of the ecosystem and supports evidence-based strategies by simulating dynamics and evaluating policy interventions.

2- 3- Modeling Steps

The study employs System Dynamics (SD) to analyze Bitcoin mining by identifying key ecosystem challenges—like energy consumption and regulatory concerns—and mapping critical variables such as profitability and energy use. Expert feedback refines the model to align with real-world dynamics. Hypotheses are developed to explore interactions between variables like mining incentives and market demand, forming causal loops and stock-and-flow diagrams. These diagrams represent feedback loops and resource flows, respectively. Mathematical relationships derived from real-world data are used to simulate scenarios, conduct sensitivity analysis, and validate results against observations. Figure 1 outlines these modeling steps.

3- Results and Analysis

3- 1- System Dynamics Model of Bitcoin Network

The causal loop model offers a structured framework for understanding the intricate relationships among various factors within the Bitcoin ecosystem. By mapping out both reinforcing and balancing feedback loops, the model captures the dynamics that drive the system's behavior over time. This interconnected network of variables creates a complex system where changes in one factor ripple through the entire network, influencing aspects such as mining profitability and Bitcoin's market value. The model's primary purpose is to

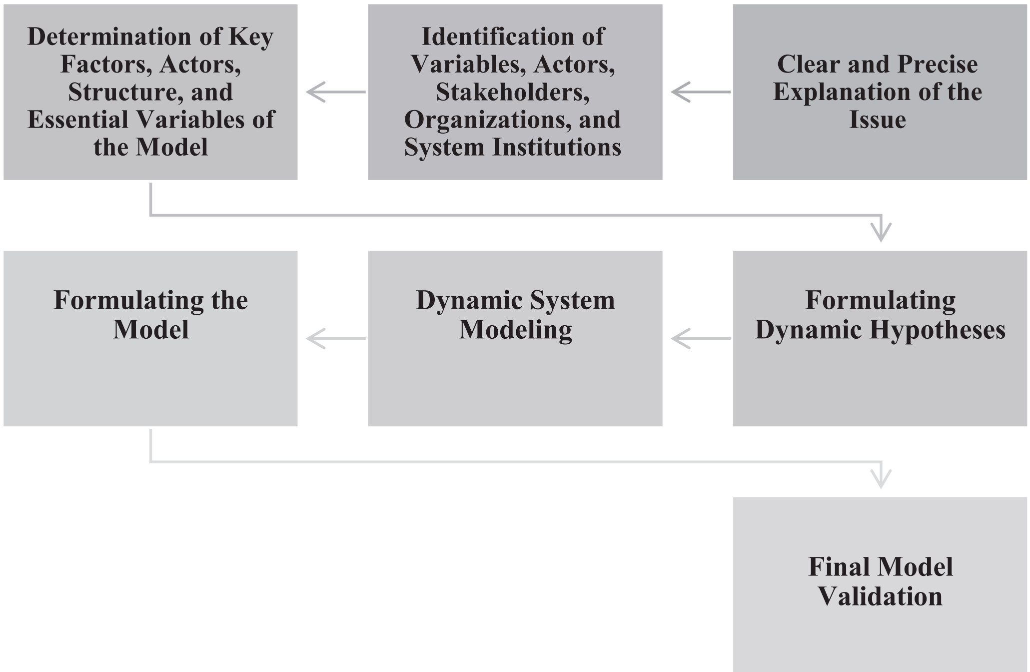

Fig. 1. Stages of the Modeling Process

provide a visual representation of how key variables interact and collectively influence the overall behavior of the Bitcoin network.

The final integrated model provides a comprehensive understanding of the Bitcoin mining ecosystem, addressing key dynamics such as investment incentives, market demand, technological advancements, mining difficulty, and energy consumption. Initially, Bitcoin's appeal is driven by its decentralized nature and the potential for high returns, with rising Bitcoin prices attracting more investors and miners. This influx increases the network hash rate and mining difficulty, reinforcing Bitcoin's value and scarcity. As mining difficulty increases, so do energy requirements, leading to higher operational costs, which in turn reduce profitability. This reduction in profitability can result in fewer miners, creating a balancing feedback loop that restores equilibrium as network difficulty adjusts.

The model further incorporates technological advancements, such as high-efficiency mining equipment, which boosts computational power and increases mining activity. As more miners enter the network, the hash rate rises, but network difficulty adjusts to maintain a steady block production rate. Additionally, the model integrates the role of Bitcoin's market value in determining mining profitability. Rising Bitcoin prices provide higher returns for miners, offsetting increasing operational costs, while transaction fees and block rewards serve as essential sources of income. However, as block rewards decrease over time due to the halving events, transaction fees become an increasingly important component of miner revenue.

Bitcoin's speculative demand adds another layer of complexity to the model. Speculators, motivated by price fluctuations, can drive short-term price increases, decoupling Bitcoin's market price from its fundamental value. While high energy costs can reduce mining activity and decrease supply, speculative demand can fuel price volatility, contributing to market unpredictability. These dynamics highlight the delicate balance that must be maintained between mining costs, speculative demand, and overall market behavior.

Mining incentives are closely linked to transaction volumes, which influence block rewards and transaction fees. As transaction volume increases, miners earn more through fees in addition to block rewards, enhancing their profitability and attracting additional miners. The halving of block rewards, occurring approximately every four years, reduces direct rewards for miners, with transaction fees becoming increasingly critical in maintaining profitability. This gradual reduction in rewards ensures that mining remains attractive as long as transaction fees are sufficient.

Lastly, the model considers the demand for Bitcoin mining, shaped by Bitcoin's use as a currency, speculative interest, and the participation of long-term believers in Bitcoin's potential. The growing use of Bitcoin in transactions increases the need for miners to process transactions and secure the network. Speculators reduce the circulating supply by holding Bitcoin, which further raises the demand for mining. Additionally, fundamentalists who view Bitcoin as a store of value contribute to the network's stability by

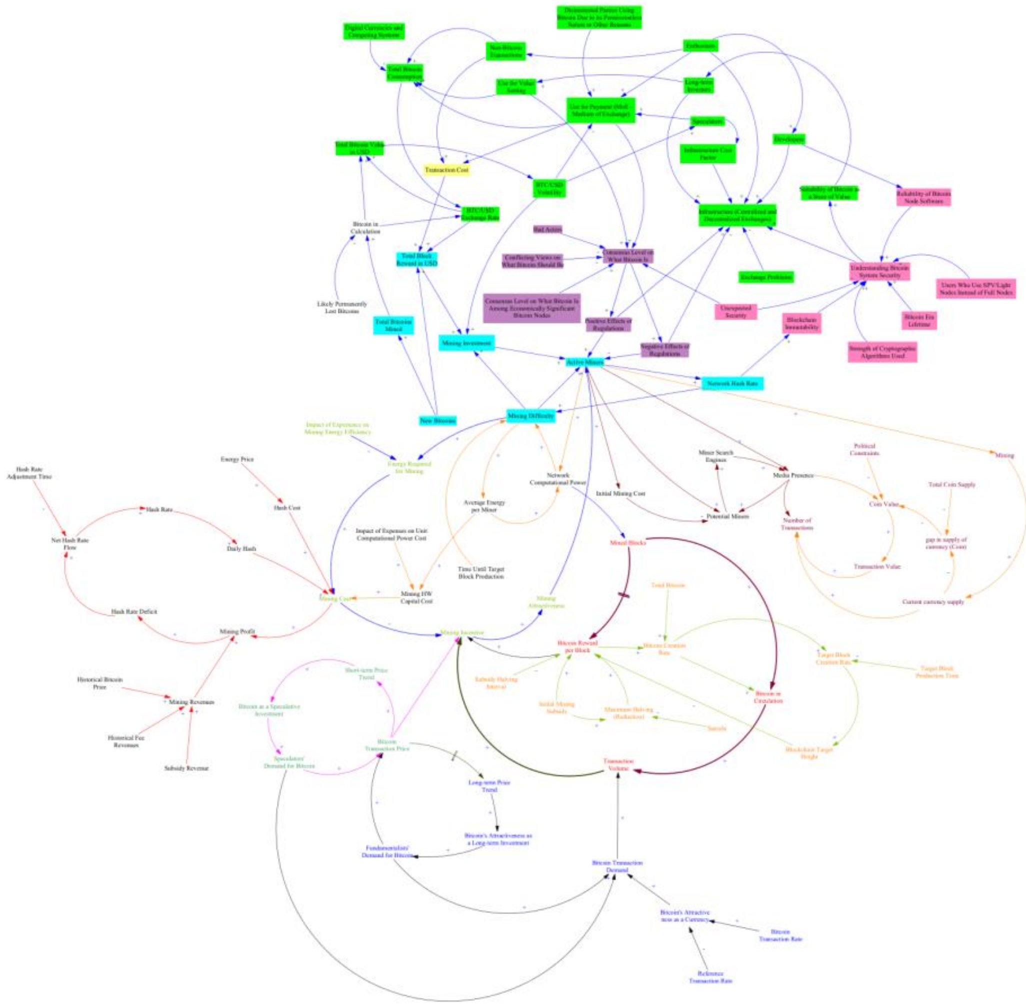

Fig. 2. Bitcoin Market Cost and Network Mining Demand Variables

maintaining a decentralized infrastructure through mining.

In conclusion, the integrated model(fig.2) highlights the interplay of these variables, offering a comprehensive framework for understanding the evolution and dynamics of Bitcoin mining. By balancing technological innovations, economic sustainability, and market behavior, the model ensures the long-term growth, stability, and profitability of Bitcoin mining, helping stakeholders make informed decisions in this rapidly evolving ecosystem.

3- 2- Introduction to the Stock and Flow Model

To streamline the discussion of Bitcoin mining dynamics, the definitions of the four subsystems (Mining, Bitcoin, Hash Rate, and Mining Difficulty) have been merged into a single section, ensuring clarity and coherence. The Mining Subsystem diagram has been selected as the representative visual, as it effectively captures the critical interactions and complexities of the Bitcoin ecosystem.

Unified Subsystem Analysis: The Mining Subsystem plays a pivotal role in understanding how economic and regulatory factors shape mining activities. This subsystem examines the influence of variables like energy costs, mining hardware expenses, and Bitcoin market price. These factors directly impact miner profitability, network participation, and the overall hash rate. Regulatory measures and market conditions also determine miner incentives, creating a balance between growth and sustainability. For example, favorable energy policies encourage mining, whereas restrictive regulations can suppress network expansion.

The Bitcoin Subsystem focuses on the flow of Bitcoins, including creation, circulation, and loss. Bitcoin issuance follows a deflationary model, with halvings reducing block rewards approximately every four years. Factors such as wallet inaccessibility further decrease the circulating supply, reinforcing Bitcoin's scarcity and its appeal as a store of value. These dynamics ensure a predictable supply trajectory,

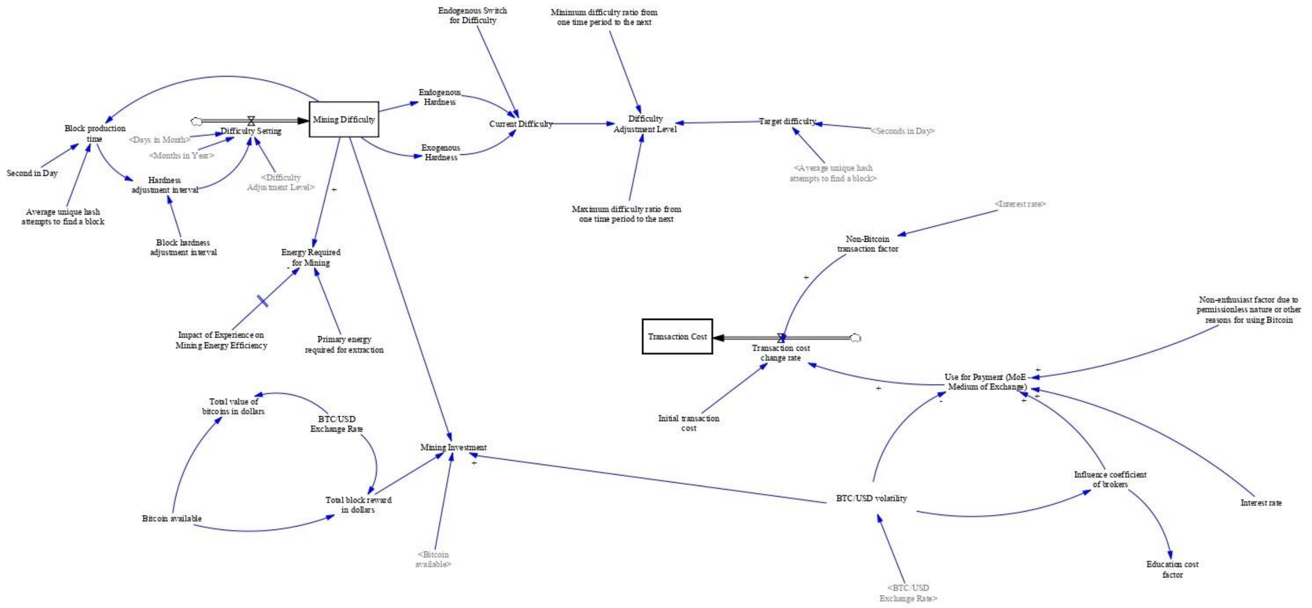

Fig. 3. Bitcoin Market Cost and Network Mining Demand Variables

essential for maintaining market confidence and long-term investment attractiveness.

The Hash Rate Subsystem is crucial for assessing the network's computational power. This subsystem demonstrates how profitability and energy costs influence miner participation, impacting the hash rate and overall network security. Increased miner participation elevates the hash rate, prompting adjustments in mining difficulty to maintain Bitcoin's 10-minute block interval. Conversely, rising energy expenses or declining Bitcoin prices can reduce the hash rate, challenging network resilience.

Finally, the Mining Difficulty Subsystem ensures network stability by dynamically adjusting mining difficulty based on changes in the hash rate. Difficulty recalibrations every 2,016 blocks maintain a consistent block production rate. This subsystem also integrates transaction fees as a supplementary incentive for miners, especially as block rewards diminish over time. Advanced hardware and energy-efficient practices allow miners to remain competitive, even under increasing difficulty.

By synthesizing the insights from these subsystems, this unified framework provides a comprehensive perspective on Bitcoin's mining ecosystem. The Mining Difficulty Subsystem diagram (Fig. 3) has been included to illustrate these interconnected dynamics, offering stakeholders actionable insights into regulatory impacts, market trends, and sustainability challenges. The subsystem highlights the dynamic recalibration processes essential for maintaining network stability and mining profitability, ensuring adaptability amidst evolving computational demands and market conditions.

3- 3- Key Variables and Mathematical Formulas Defining the Bitcoin Mining Ecosystem

In order to model the dynamics of the Bitcoin mining ecosystem, several key variables and their relationships play a pivotal role in determining the system's behavior (Table 2). These variables represent different components of the mining process, from hash rate and mining costs to revenues and Bitcoin price dynamics. The interactions between these variables allow for a comprehensive understanding of the factors influencing mining profitability, network security, and market demand.

The formulas presented in the following table were developed by synthesizing insights from foundational works in the field, including Nakamoto (2009)[1], Zhou et al. (2020) [15], Sterman (2000) [16], and others. These references provided conceptual frameworks and methodologies that informed the mathematical representation of variables such as hash rate adjustments, energy costs, and mining profitability. By integrating these elements into the system dynamics (SD) model, this study ensures a robust and empirically grounded analysis of the Bitcoin ecosystem. The variables and formulas selected highlight their direct impact on the key processes within the ecosystem and their ability to drive meaningful insights from the model's simulation.

The variables presented in the table above form the core structure of the system dynamics model, allowing us to simulate the Bitcoin mining ecosystem under various scenarios. By using these key formulas, the model captures the interactions between mining costs, hash rate, Bitcoin price fluctuations, and speculative demand. These interactions are crucial for understanding the long-term behavior of the

Table 2. Key Variables and Mathematical Formulas

Variable	Formula
Hash Rate Adjustment Time	Hash Rate Adjustment Time = (Current Difficulty × Target Block Time) / Current Hash Rate
Net Hash Rate Flow	Net Hash Rate Flow = Incoming Hash Rate - Outgoing Hash Rate
Hash Rate	Hash Rate = Number of Hashes / Time Taken
Hash Rate Deficit	Hash Rate Deficit = Required Hash Rate - Current Hash Rate
Daily Hash	Daily Hash = Hash Rate × Number of Seconds in a Day
Hash Cost	Hash Cost = (Energy Cost + Hardware Cost) / Total Hashes
Energy Price	Energy Price = Total Energy Cost / Energy Consumed
Mining Profit	Mining Profit = Mining Revenue - (Energy Cost + Depreciation Cost)
Mining Revenues	Mining Revenues = (BTC Mined × Bitcoin Price) + Transaction Fees

network and predicting how changes in one variable can impact the entire ecosystem.

The selected formulas not only reflect the fundamental dynamics of Bitcoin mining but also ensure that the model remains computationally feasible while providing valuable insights into the economic and technical challenges faced by the network. By incorporating these variables, the model helps to identify critical leverage points and evaluate the sustainability of Bitcoin mining operations under different market conditions.

3- 4- The defining of scenarios

Table 3 outlines various scenarios and their associated states, focusing on key variables within the Bitcoin mining ecosystem. A scenario represents a broader condition modeled to explore the impact of specific factors such as technology, regulation, or market trends, while a state refers to different configurations within a scenario that captures variations in system behavior based on technological, economic, or policy changes. Each scenario includes its definition, key assumptions, and the rationale for examining the chosen variable. By analyzing multiple states within each scenario, this table provides insights into the dynamics of Bitcoin mining, offering a structured foundation for decision-making and policy evaluation

3- 5- ScenarioAnalysis

3- 5- 1- Scenario 1:Impact of Increase in the Number of Miners on Bitcoin Mining Rate

In this scenario, we analyze the impact of an increasing number of miners on Bitcoin mining rates across three distinct states (Figure 4), each reflecting different market dynamics influenced by technological advancements, economic conditions, and external factors.

State 1 represents steady mining activity with a gradual increase in the number of miners, reflecting stable market conditions. There are no major technological disruptions or external incentives. Mining remains profitable but grows slowly, emphasizing market resilience and sustainability without rapid expansion.

Table 3. The defining of scenarios

Scenario	Scenario Definition and Rationale (with references)	Assumptions	Key Variables	Reason for Choosing the Variable	Reason for Different States and How They Are Implemented in the Model	Reason for Examining This Scenario
Scenario 1: Increase in the Number of Miners	This scenario is designed to examine the impact of an increasing number of miners on Bitcoin mining rates. Relevant references include the "Parliament Research Center (2017)" and "Cabinet Resolution (2021)," which emphasize the sustainability of mining and the influence of miner participation.	It is assumed that the growth in the number of miners directly increases Bitcoin mining rates, and this increase creates different network behaviors depending on the rate of growth.	Bitcoin Mining Rate	The Bitcoin mining rate variable is chosen for its importance in ensuring network sustainability and resource production. It is one of the key factors for regulating Bitcoin production rates and ensuring network security.	This Scenario includes three states: 1.**Current Model Trend**: This state assumes a constant number of miners, using historical data and projected growth rates with no changes in input parameters. **2. Gradual Increase in Miners**: In this state, miners grow at a linear rate, with adjustments in network hash rate and mining difficulty as more miners join each month.**3. Rapid Increase in Miners**: Here, the number of miners increases exponentially due to factors like equipment deployment or financial incentives. This leads to a sharp rise in network difficulty and reduced profitability over time.	This scenario helps policymakers evaluate the effects of an increasing number of miners on network sustainability and security, enabling them to develop strategies for managing miner growth.
Scenario 2: Equipment and Network Difficulty	This scenario examines the impact of various types of equipment and changes in network difficulty on the number of Bitcoins mined. Relevant references include the "National Cyberspace Center (2021)" and the "Cabinet Resolution (2018)," which emphasize the importance of advanced equipment and network difficulty in ensuring ecosystem security and sustainability.	It is assumed that mining equipment and network difficulty have a direct effect on mining rates and the number of Bitcoins produced.	Number of Bitcoins Mined	The variable "number of Bitcoins mined" is key for analyzing the direct impact of changes in network difficulty and equipment levels on network profitability and sustainability.	Three states are implemented in the model: 1. Current Model Trend: The model assumes equipment remains at current levels, and network difficulty changes naturally (based on current hash rates). 2. Standard Equipment with Increased Network Difficulty: The model assumes mid-level equipment is used, and network difficulty dynamically increases with the number of miners. These changes result in reduced profitability over time and increased block production times. 3. Outdated Equipment with Fixed Network Difficulty: In this state, outdated equipment is used, and network difficulty does not change, leading to slower mining rates and delayed block production.	This scenario helps analyze the role of equipment and network difficulty in improving mining efficiency and maintaining network securit
Scenario 3: Impact of Technology and Gradual Growth on Hash Rate	This scenario examines the effect of two different trends, namely "rapid adoption of new technologies" and "gradual miner growth," on the network's hash rate. Relevant references include "Parliament Research Center (2017)" and "National Cyberspace Center (2021)," which emphasize the importance of technology and miner behavior in ensuring network security.	It is assumed that the hash rate is influenced by the speed of technology adoption and the gradual increase in the number of miners. Rapid technological growth quickly increases the hash rate, whereas gradual miner growth results in a slower but more stable increase in the hash rate.	Current Hash Rate	The variable "hash rate" is critical for evaluating network security and mining efficiency across different levels of technology and miner growth.	Three states are implemented in the model: 1. Current Model Trend: The hash rate remains constant and is simulated based on historical data. 2. Rapid Adoption of New Technologies: In this state, the hash rate increases exponentially as advanced equipment is introduced, improving network efficiency. 3. Gradual Growth in Miner Numbers: This state simulates a linear increase in the number of miners, leading to a slower and more sustainable growth in the hash rate.	This scenario helps policymakers understand the effects of technology and miner behavior on the security and sustainability of the Bitcoin network.
Scenario 4: The Impact of Technology Growth and a Balanced Approach on Mining Difficulty	This scenario analyzes how Bitcoin mining difficulty changes under the influence of technology growth and balanced approaches. Relevant references include the "Parliament Research Center (2017)" and "National Cyberspace Center (2021)," which emphasize the importance of managing network growth and technology to ensure network security.	It is assumed that technology growth directly increases network difficulty, while a balanced approach may control the rate of difficulty changes.	Mining Difficulty	Mining difficulty is essential for ensuring network security and regulating Bitcoin production rates. This key variable is directly affected by technology and the number of miners.	Three states are implemented in the model: 1. Current Model Trend: Mining difficulty naturally adjusts based on historical data and current hash rates. 2. Rapid Technology Growth: This state simulates a sharp increase in difficulty due to the introduction of advanced equipment and higher hash rates. 3. Balanced Growth: In this state, mining difficulty increases more gradually to maintain network stability. It assumes that new equipment is introduced incrementally and hash rate growth is controlled.	This scenario helps policymakers understand the effects of rapid technology growth and balanced strategies on network security and sustainability.

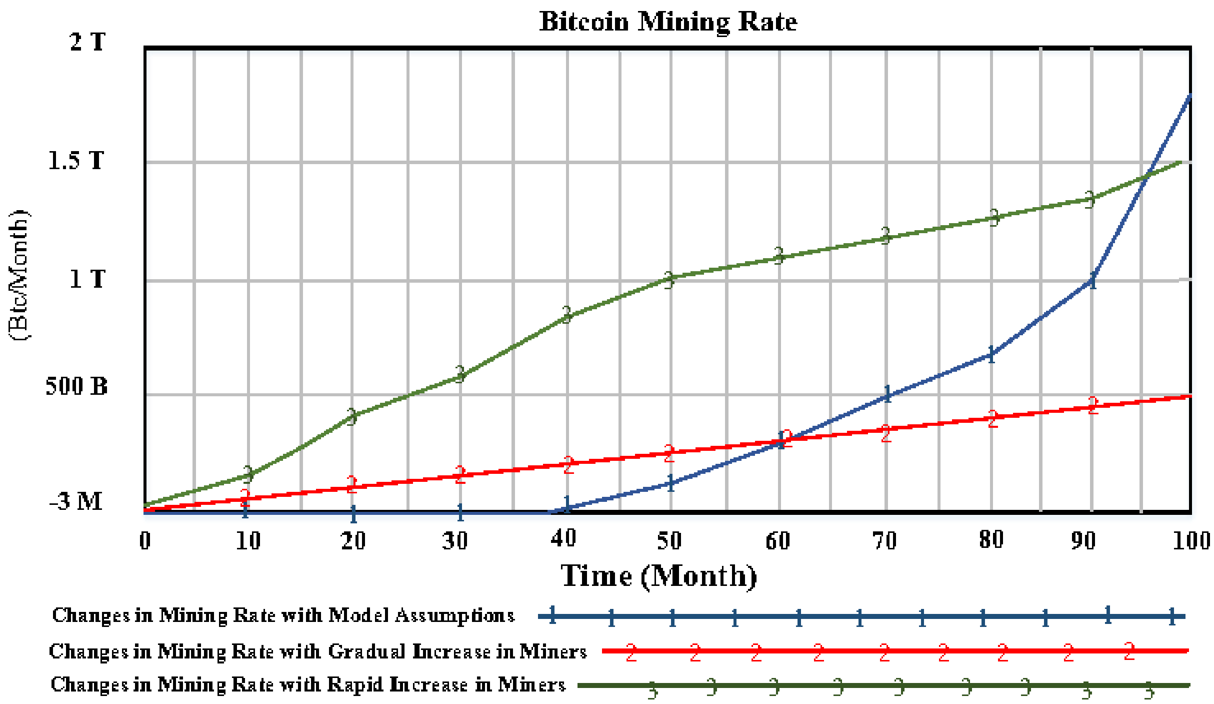

Fig. 4. Comparison of Bitcoin mining rates under gradual, moderate, and rapid miner growth scenarios.

State 2 sees a moderate increase in miners, driven by incremental technological advancements and improved equipment. This results in a stable, but slightly faster growth rate compared to State 1, emphasizing consistent productivity and stability without oversaturation or major disruptions.

State 3 captures a sharp increase in miner participation due to strong economic incentives and rapid adoption of advanced technologies. This leads to an initial surge in the mining rate, reaching a peak of 1 trillion BTC per month by month 50 (Figure 4, green line). However, the growth slows over time due to rising operational costs, energy consumption, and market saturation, stabilizing at 500 billion BTC per month by month 100.

The comparative analysis of these states highlights the differences in mining growth dynamics. **State 1** offers steady long-term growth, reaching 1.75 trillion BTC per month by month 100 (Figure 4, blue line), with resilience but limited potential for rapid expansion. **State 2** shows a controlled, stable increase in miners, reaching 1.5 trillion BTC per month by month 100 (Figure 4, red line), ensuring consistent growth with minimal volatility. **State 3**, driven by rapid miner participation and technological adoption, sees an initial surge but stabilizes at 500 billion BTC per month due to market saturation and higher operational costs.

From a strategic perspective, each state offers distinct insights. **State 1** and **State 2** highlight the trade-off between stability and growth. Both emphasize controlled expansion, minimizing market risks, and avoiding the resource strain that comes with rapid growth. While they promote sustainability, they may miss opportunities for accelerated growth. In contrast, **State 3** capitalizes on rapid expansion but introduces risks related to sustainability, energy consumption, and heightened competition.

State 3 particularly emphasizes the need for operational flexibility in managing rapid growth. As mining activity surges, the network must adapt to higher costs and energy requirements. This state illustrates how unchecked expansion can lead to inefficiencies, making proactive infrastructure and resource management critical. **Cost management** is a key theme across all three states, with the ability to control operational expenses—such as energy costs and hardware investments—being essential for maintaining profitability and long-term network health. **State 3** underscores how rapid scaling can increase costs, emphasizing the need for a comprehensive cost strategy for sustainable growth.

In conclusion, this analysis underscores the complexity of managing growth in the Bitcoin mining ecosystem. Technological innovation and miner participation can fuel rapid expansion, but these benefits must be weighed against the risks of rising costs and diminishing returns. **State 1** and **State 2** offer lessons on strategic, gradual growth, while **State 3** illustrates both the potential and challenges of rapid

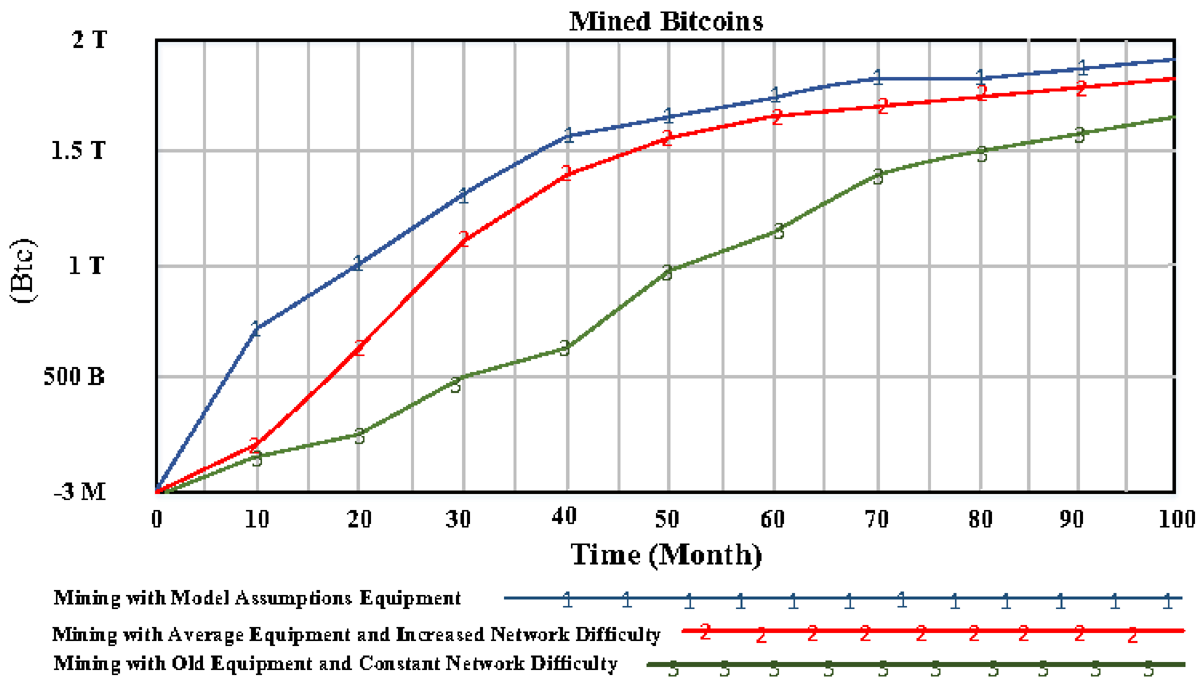

Fig. 5. Effects of mining equipment and network difficulty on Bitcoin production, showing supply growth under modern, average, and outdated equipment scenarios.

expansion. Stakeholders should prioritize adaptive planning, cost optimization, and infrastructure scalability to ensure the Bitcoin mining network's long-term sustainability and profitability.

3- 5- 2- Scenario 2: Impact of Equipment and Network Difficulty on Number of Bitcoins Mined

In this scenario, we analyze how different mining equipment and network difficulty levels impact the total number of Bitcoins mined over time (Figure 5). The three distinct states show how technological advancements, mining equipment, and difficulty interact to influence Bitcoin's mining rate and total supply.

State 1: Current Model with Modern Equipment

In this state, mining uses state-of-the-art equipment that adapts to increasing network difficulty. The mining activity starts with rapid growth, enabled by advanced technology for efficient block solving. By month 50, the total mined Bitcoin reaches 1.7 trillion BTC, and by month 100, it stabilizes at 1.9 trillion BTC. While initial growth is fast, it slows as difficulty increases, reflecting Bitcoin's deflationary nature. The difficulty rises limits mining speed as the supply cap nears.

State 2: Average Equipment with Increased Difficulty

This state uses average equipment, which performs well but is not as efficient as in State 1. As network difficulty increases, the mining rate slows accordingly. By month 50, 1.6 trillion BTC is mined, and by month 100, it reaches 1.7 trillion BTC. This state shows steady growth, where mining adapts gradually to increased difficulty. The growth is predictable and avoids the extremes of rapid growth or stagnation, making it more balanced and sustainable.

State 3: Old Equipment with Constant Difficulty

In this state, outdated mining equipment is used, and network difficulty remains constant. The slower mining efficiency leads to reduced Bitcoin production. By month 50, the total mined Bitcoin reaches 1 trillion BTC, and by month 100, it reaches 1.6 trillion BTC. This scenario illustrates the consequences of technological stagnation, where the inability to keep up with advancements slows production and delays hitting the Bitcoin supply cap.

The comparative analysis of these three states highlights the crucial role of technology and network difficulty in shaping Bitcoin's mining dynamics.

State 1 (Current Model with Modern Equipment) shows rapid early growth driven by technological advancements. However, as mining difficulty increases, growth slows and stabilizes at 1.9 trillion BTC by month 100. This state represents efficient mining but emphasizes the eventual slowdown as the Bitcoin supply approaches its cap.

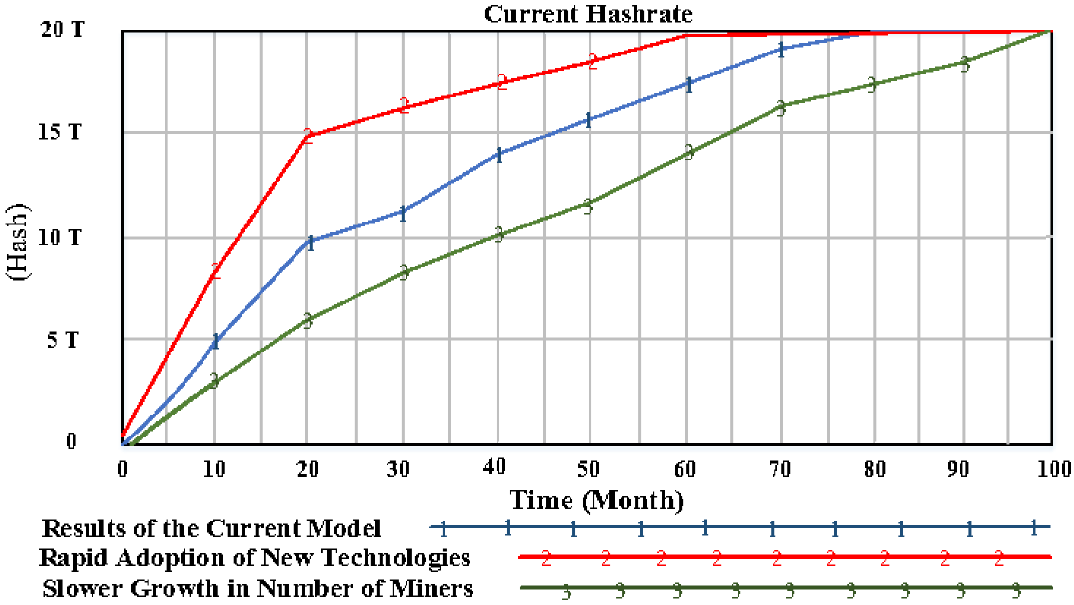

Fig. 6. Hash rate growth in Bitcoin mining under three scenarios: current trend, rapid adoption of new technologies, and slow growth in the number of miners.

State 2 (Average Equipment with Increased Difficulty) shows moderate and consistent growth, with 1.7 trillion BTC mined by month 100. This state reflects a balance between technological capability and increasing difficulty, enabling predictable, sustainable growth.

State 3 (Old Equipment with Constant Difficulty) highlights the limitations of outdated technology, resulting in much slower production, with only 1.6 trillion BTC mined by month 100. This scenario illustrates how technological stagnation can hinder mining efficiency and delay reaching the supply cap.

These insights emphasize the importance of keeping pace with technological advancements and network changes to maintain profitable mining operations. As the Bitcoin network evolves, miners must adapt to increasing difficulty and leverage modern technologies to remain competitive. For policymakers and investors, understanding these dynamics is critical for evaluating the broader implications of mining efficiency, network difficulty, and supply growth in the Bitcoin ecosystem.

3- 5- 3- Scenario 3: Impact of Technology and Gradual Growth on Hash Rate

The **hash rate** of the Bitcoin network is a key metric for understanding its computational capacity, security, and overall mining activity. This scenario explores how factors such as technological advancements and miner participation affect hash rate growth and its impact on network performance (Figure 6).

State 1: Current Model

In this state, mining operates under normal conditions, with gradual improvements in technology. The hash rate increases steadily over time due to incremental equipment upgrades and consistent miner participation. By month 50, the hash rate reaches 16 terahashes per second (TH/s), and by month 60, it rises to 17 TH/s. This state represents sustainable growth, ensuring the network maintains security and efficiency without drastic energy spikes or volatility.

State 2: Rapid Adoption of New Technology

In this state, the rapid adoption of high-performance mining hardware leads to a sharp increase in the hash rate. By month 50, the hash rate reaches 17 TH/s, and by month 60, it grows to 20 TH/s. This growth enhances network security, allows the network to process more transactions, and better resists threats. However, the rapid growth increases energy demands, raising concerns about environmental sustainability, which becomes a critical issue for the network's future.

State 3: Slow Growth in Number of Miners

In this state, slow miner growth, due to economic factors, market barriers, or regulations, results in a more gradual increase in the hash rate. By month 50, the hash rate reaches 12 TH/s, and by month 60, it reaches 14 TH/s. This slow pace avoids excessive resource strain and market oversaturation but may reduce the network's competitiveness. The slower growth could make the network more vulnerable to external pressures, reducing its ability to quickly adapt to market demands or security threats.

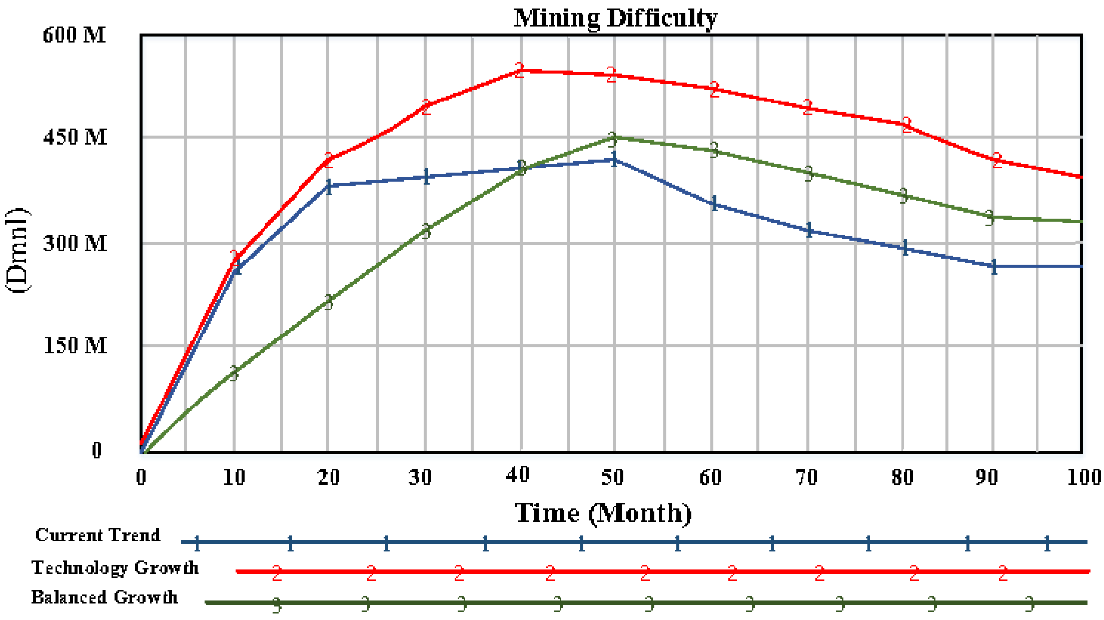

Fig. 7. Impact of technology growth and mining difficulty on Bitcoin mining, showing the trajectory of mining difficulty under current trends, rapid technological adoption, and a balanced growth approach.

A comparative analysis of the three states highlights the trade-offs between growth speed, network security, and sustainability in Bitcoin's hash rate development.

State 1 (Current Model) shows steady, predictable growth in the hash rate. By month 50, the hash rate reaches 16 TH/s, and by month 60, it increases to 17 TH/s. This gradual increase, driven by equipment improvements and stable market conditions, ensures efficiency and security without rapid acceleration. The advantage of this state is its stability, avoiding volatility or unsustainable energy consumption, which supports long-term network stability.

State 2 (Rapid Adoption of New Technology) demonstrates the benefits of rapid technological adoption. The hash rate jumps to 17 TH/s by month 50 and reaches 20 TH/s by month 60. This state illustrates how technological innovation can significantly enhance mining efficiency and security. However, the sharp rise in hash rate raises concerns about energy consumption and operational costs. As hardware improves, the network faces sustainability challenges that must be managed for long-term viability.

State 3 (Slow Growth in Number of Miners) shows the effects of slow miner participation. By month 50, the hash rate reaches 12 TH/s, and by month 60, it increases to 14 TH/s. This slow growth emphasizes sustainability, avoiding resource strain but reducing competitiveness. The network's slower expansion limits its ability to quickly adapt to market demands or security threats, potentially weakening its resilience.

The analysis underscores the need for a balance between technological innovation, miner participation, and sustainability to ensure the long-term security and efficiency of the Bitcoin network. **State 2** highlights the benefits of rapid technological adoption but also the challenge of managing energy consumption. **State 1** focuses on stability and steady growth, while **State 3** illustrates how slow growth may enhance sustainability at the cost of reduced competitiveness.

For stakeholders, the key takeaway is the importance of maintaining technological innovation and growth while managing energy efficiency and market saturation. Policymakers, miners, and investors must consider these factors when developing strategies for the Bitcoin network's security, efficiency, and sustainability.

3- 5- 4- Scenario 4: Impact of Technology Growth and a Balanced Approach on Mining Difficulty

Mining difficulty is a crucial factor in the Bitcoin ecosystem, determining the computational power required to mine new blocks. It evolves dynamically, influenced by technological advancements, network growth, and miner participation. In this scenario, we examine three states that represent how these factors shape mining difficulty over time (Figure 7).

State 1: Current Trend

In this state, mining difficulty increases steadily, with a sharp rise initially followed by a gradual decline as the market matures. By month 50, the difficulty reaches 410 million difficulty hashes (Dmh), and by month 100, it drops to 280 million Dmh. This reflects the natural progression of a maturing market, where mining activity slows as resources become fully utilized and technology reaches its limits. The decline in difficulty indicates that some miners exit the network due to reduced profitability or outdated equipment, leading to lower competition and computational demand.

State 2: Technology Growth

This state reflects the rapid adoption of advanced mining technologies, driving a faster increase in mining difficulty. By month 50, the difficulty rises to 530 million Dmh, and by month 100, it decreases to 390 million Dmh. The initial rise in difficulty is sharper due to competition spurred by high-efficiency equipment. As mining technologies extend the lifespan of operations, the decline in difficulty slows, and the network stabilizes. This state illustrates the transformative power of technological innovation, which accelerates short-term mining activity while improving long-term stability and efficiency.

State 3: Balanced Growth

In this state, mining difficulty increases gradually, reflecting steady market growth without rapid technological shifts. By month 50, the difficulty reaches 450 million Dmh, and by month 100, it drops to 320 million Dmh. This state represents a sustainable growth model, where new miners enter the network at a steady pace, and older equipment continues contributing. The gradual difficulty increase ensures stability and adaptability, avoiding sharp fluctuations and providing a long-term, sustainable trajectory for Bitcoin mining.

A comparative analysis of these three states reveals distinct pathways for how mining difficulty evolves over time.

State 1 (Current Trend) shows a typical market progression where mining difficulty rises steadily, reaching 410 million Dmh by month 50, and then gradually decreases to 280 million Dmh by month 100. This state reflects how mining difficulty increases as more miners join, but as profitability declines and technology matures, the difficulty decreases. This pattern highlights the market's natural maturation and the eventual exit of some miners as costs rise and competition lessens.

State 2 (Technology Growth) illustrates how rapid technological adoption accelerates mining difficulty growth. Difficulty spikes to 530 million Dmh by month 50, then declines to 390 million Dmh by month 100. The initial surge in difficulty is driven by new, more powerful mining technologies, increasing competition. However, these technologies stabilize the network in the long run, slowing the decline in difficulty and promoting a more sustainable mining environment.

State 3 (Balanced Growth) emphasizes a more sustainable and gradual increase in mining difficulty. The difficulty rises steadily to 450 million Dmh by month 50 and decreases slowly to 320 million Dmh by month 100. This state reflects a more conservative approach to mining, with steady network growth and no major technological disruptions. This gradual increase helps maintain long-term stability, avoiding the volatility seen in the other states.

These insights underscore the importance of balancing technological growth with sustainability in Bitcoin mining. **State 2 (Technology Growth)** demonstrates the benefits of rapid technological adoption for short-term growth but raises concerns about energy consumption and market saturation. **State 3 (Balanced Growth)** prioritizes long-term stability, avoiding the volatility and resource strain of rapid technological adoption, though it leads to slower growth. Understanding these dynamics helps stakeholders align their strategies with evolving mining difficulties and market conditions in the Bitcoin ecosystem.

4- Conclusion

The analysis of Bitcoin's mining ecosystem reveals that managing the balance between technological innovation, mining participation, and sustainability is critical for ensuring the network's long-term security and efficiency. The scenarios presented in this study highlight different pathways for the evolution of Bitcoin mining, each with its own implications for network growth, energy consumption, and market dynamics.

In the **first scenario**, gradual growth and stable mining conditions reflect a predictable increase in mining difficulty over time. This stability ensures the network remains resilient, minimizing volatility and resource strain, but at the cost of slower growth and limited scalability. On the other hand, **scenario two** emphasizes the benefits of rapid technological adoption, driving short-term growth and increased network security. However, the risks of higher energy consumption and potential market oversaturation make long-term sustainability a concern. In contrast, **scenario three** prioritizes long-term stability with a gradual approach to growth, avoiding rapid technological disruptions and ensuring sustainability, though at the expense of competitiveness and responsiveness to market shifts. Finally, **scenario four** illustrates how technological advancements can spur rapid growth, but this must be managed carefully to avoid excessive resource use and diminishing returns as the mining network expands.

These findings underscore the complexity of managing Bitcoin's mining ecosystem, where rapid technological innovation can drive growth but introduces challenges such as energy consumption, market saturation, and competition. On the other hand, slower growth offers stability but may limit scalability and responsiveness to evolving market conditions. For policymakers, miners, and investors, it is crucial to develop strategies that balance technological growth with sustainable practices.

To address the complexities and inconsistencies in digital currency policymaking, a unified approach is necessary. Currently, the lack of consensus among policymaking bodies leads to fragmented governance and contradictory policies. Policymakers should work towards creating a comprehensive vision for the role of digital currencies, informed by emerging trends and technological developments. If digital currencies gain significant traction, a dedicated policymaking body, possibly under the Vice Presidency for Science and Technology, should be established to coordinate efforts and ensure a cohesive governance framework. This committee should include key stakeholders, such as the Central Bank, the Ministry of Energy, and the Ministry of Industry, to foster collaboration and achieve balanced policies that benefit both the government and private sectors.

In terms of regulation, it is essential to address energy-intensive mining practices. The Ministry of Energy should prioritize policies that encourage the use of renewable energy sources and off-peak mining operations. Encouraging mining centers to operate during non-peak hours can help stabilize the national grid, reduce strain on existing infrastructure, and make the industry more sustainable. Additionally, mining equipment standards should be updated regularly to promote efficiency, and a comprehensive taxation system should be implemented to address the production, holding, and exchange of digital currencies.

Finally, public education and awareness campaigns are crucial for ensuring that society fully understands digital currencies, blockchain technology, and the implications of their adoption. These initiatives can help reduce risks of misuse and foster informed public engagement.

In conclusion, managing the Bitcoin mining ecosystem requires a holistic approach that integrates technological innovation, sustainability, and regulatory oversight. By aligning these factors, stakeholders can ensure the long-term growth and stability of the Bitcoin network while addressing environmental, economic, and social challenges. Coordinated governance and a clear framework will enable the country to foster innovation in digital currencies while safeguarding broader societal and economic interests.

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