Bitcoin Halving Events: Historical Analysis and Strategic Insights for Miners in 2024

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***Abstract*—The upcoming fourth halving event in April 2024 introduces heightened complexity to the landscape of Bitcoin mining, necessitating a reevaluation of the sustainability of the blockchain ecosystem. Focusing on maintaining incentives becomes paramount for miners as mining rewards undergo reduction. This paper delves into the intricate dynamics of mining incentives, drawing on data from previous halving events to explore the nuanced relationship between mining rewards, cryptocurrency prices, and operational costs. Furthermore, the previous research focused on retrospectively studying halving events, while our research takes a forward-looking perspective, aiming to provide new insights by predicting future outcomes. The analysis, based on ARIMA, Linear Regression, and Random Forest, anticipates a decline in mining revenue ranging between 2.91% and 69.95%, reducing from 266,409 USD to a range between 79,984 and 258,394 USD per block following the 4th halving event. The cryptocurrency price needs to reach a minimum of 69,832 USD to sustain pre-halving revenue levels. However, the expected increase in Network Difficulty, leading to a proportional rise in mining energy costs, underscores the need for miners to focus not only on revenue sustainability but also on optimising energy costs for a healthy net profit margin.**

***Index Terms*—Blockchain, Cryptocurrency, Mining Profitability, Halving Events, Revenue Forecasting, Sustainable Mining**

I. Introduction

The exponential growth of blockchain technology has sparked significant academic interest in unraveling the complexities of blockchain mining profitability. Serving as the cornerstone of decentralised systems, mining plays a crucial role in ensuring transactional security and upholding the unassailable integrity of the blockchain. Despite its paramount importance, the cost-effectiveness of mining operations and the multifaceted factors shaping profitability continue to be subjects of immense scholarly significance and ongoing research. The dynamic interplay between technological advancements, operational efficiency, and market fluctuations instills a sense of curiosity and excitement within the academic community, driving them to decode the enigma of blockchain mining's economic viability and its broader implications for the future of the digital economy.

Mining holds a pivotal position within the Bitcoin blockchain ecosystem, playing a central role in facilitating the operation and security of the entire network. Miners, the key actors in this process, engage in a competitive and intricate task of solving complex mathematical puzzles through the Proof of Work mechanism to validate and create new blocks [1].

As a reward for their successful efforts, miners gain the privilege to create new blocks and are granted a certain amount of newly minted Bitcoins. However, this process is not without its intricacies. With the occurrence of each halving event, the mining rewards undergo a reduction, leading to a gradual decrease in the total supply of newly created Bitcoins. The fourth Bitcoin subsidy halving event stands as a crucial milestone in the ongoing development of the Bitcoin ecosystem. Existing research [2, 3] on Bitcoin halving events has primarily focused on retrospective analysis, overlooking the crucial aspects of predicting and preparing for future events.

In anticipation of the forthcoming 2024 Bitcoin halving event, which will reduce block rewards from 6.25 BTC to 3.125 BTC, miners face the challenge of sustaining revenue levels. To address this, our research provides a quantitative analysis of the impact of the next Bitcoin halving event based on historical data, offering strategic insights for miners. Anticipating up to a 183% surge in Bitcoin price with advanced forecasting models such as AutoRegressive Integrated Moving Average (ARIMA), Linear Regression, and Random Forest, driven by positive market sentiment and institutional interest, is crucial for maintaining or enhancing revenue. These models offer diverse perspectives on Bitcoin market trends, allowing us to make informed predictions about future scenarios. The revenue expectation table underscores the need for Bitcoin prices to attain a minimum of 69,832 USD to sustain pre-halving revenue levels. This comprehensive analysis guides miners in navigating the post-halving landscape, emphasizing the importance of not only revenue sustainability but also the optimisation of energy costs for a healthy net profit margin.

The contribution of our research can be summarised into three key aspects:

- Comprehensive Historical Analysis: The study contributes through a detailed historical analysis of Bitcoin halving events, exploring key metrics and uncovering insights into the complex dynamics of Bitcoin's transactional, economic, and market behaviors.
- Predictive Models for Mining Revenue: The study uses advanced models (ARIMA, Linear Regression, Random

Forest) to forecast the effects of the April 2024 Bitcoin halving on mining revenue.
- Strategic Considerations for Miners: The study guides miners on adapting to reduced subsidies and rising competition, emphasizing efficiency, elastic mining models, and sustainability. Offering insights into the evolving cryptocurrency mining landscape, it equips miners with valuable information to optimise operations, address environmental concerns, and sustain profitability amid changing industry dynamics.

The subsequent sections of this paper are organised as follows. In Section II, an in-depth exploration of blockchain technology and the Bitcoin halving event is provided. Section III reviews the existing literature related to past halving events. Section IV focuses on the data analysis of historical halving events, investigating the relationship between cryptocurrency prices and reward reductions. Subsequently, Section V delves into observations regarding the upcoming halving event expected around April 2024 based on the data analysis in the previous section. This information is then used to analyse profitability, leading to a comprehensive discussion of the findings. Finally, Section VI summarises the outcomes and outlines potential directions for future research.

II. Background

This section provides an overview of the blockchain and mining, followed by an explanation of the Bitcoin halving mechanism and its significance in controlling coin supply and inflation.

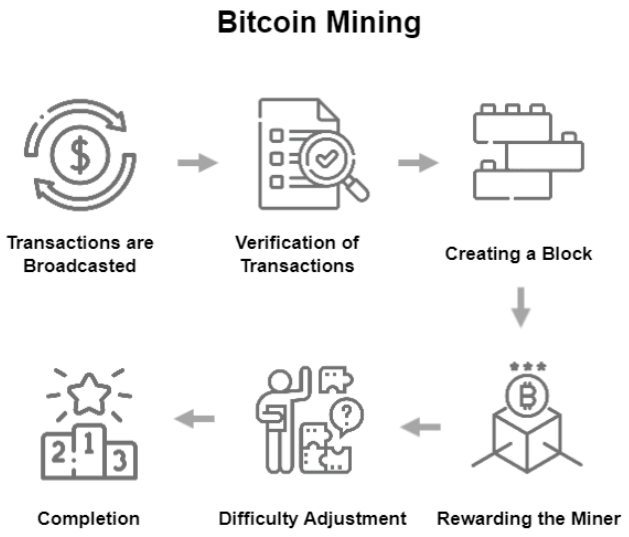

Fig. 1. Bitcoin Mining Process [4]

A. Blockchain and Mining

Blockchain is a foundational technology underlying cryptocurrencies and various decentralised applications. It functions as a distributed, immutable ledger that records transactions across a network of interconnected nodes. Each transaction is grouped into a block cryptographically linked to the previous block, forming a chain of blocks, hence the term ”blockchain.” This structure ensures transparency, security, and tamper resistance, making it vital in revolutionizing digital transactions and data management across industries [1].

Figure 1 illustrates the fundamental process of blockchain mining in the operation and maintenance of the blockchain network. Miners with powerful computational resources compete to solve complex mathematical puzzles through the Proof of Work consensus mechanism. The first miner to solve the puzzle successfully earns the right to validate and append the block of transactions to the blockchain. As a reward for their efforts and resources expended, miners are granted new coins, known as block rewards, which constitute the primary source of newly minted cryptocurrencies. It also plays an essential role in issuing new cryptocurrency units through mechanisms like proof-of-work. Mining’s energy-intensive nature has sparked discussions on environmental sustainability and alternative consensus mechanisms [5].

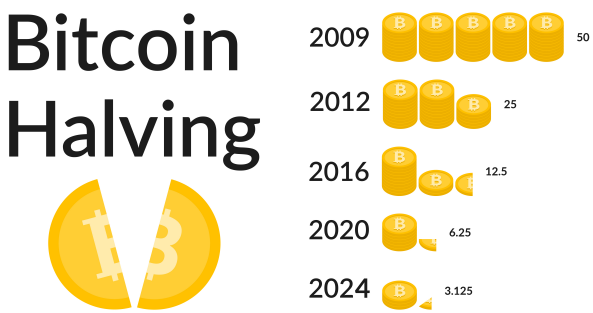

Fig. 2. Bitcoin Halving Event [6]

B. Transaction Fees

Bitcoin transaction fees are vital for the cryptocurrency ecosystem, incentivizing miners and ensuring network security. Users can add fees to expedite transactions, with higher fees leading to quicker confirmations and lower fees potentially causing delays during network congestion [7, 8]. Factors like transaction size and network demand influence fees, creating competition among users. Those offering higher fees experience faster transaction processing, particularly when demand for block space is high [9].

C. The Significance of Halving Events

The Bitcoin halving mechanism is an essential and inherent feature of the protocol, designed to control coin supply and inflation over time. Approximately every four years, or after 210,000 blocks, the mining reward is halved as described in Figure 2. This event, known as the halving, reduces the rate at which new Bitcoins are created, contributing to a controlled and predictable issuance schedule.

The occurrence of halving events has a profound impact on the dynamics of the Bitcoin ecosystem, particularly concerning mining incentives. Some might speculate that miner incentives

would diminish as mining rewards decrease during halving events. However, historical data from previous halvings reveals a fascinating paradox. Despite the reduction in rewards, the price of Bitcoin has historically tended to increase following halving events [10]. This price appreciation not only offsets the reduction in block rewards but also enhances mining incentives, effectively encouraging miners to continue their operations and support the network.

Understanding this interplay between mining rewards, cryptocurrency price, and miner incentives is crucial in assessing the sustainability and longevity of the Bitcoin network. By delving into historical data and analyzing the complexities surrounding halving events, this paper aims to provide valuable insights into the mechanisms that drive mining incentives and their implications for the broader cryptocurrency ecosystem.

III. Related Work

To contextualise our research, we review existing literature on previous halving events and their implications for mining incentives. We identify gaps in the research landscape that our study aims to address.

Meynkhard [2] reviewed existing literature on previous halving events and their implications for mining incentives, identifying research gaps. It built upon prior studies by investigating the fair market value of Bitcoin and its correlation with halving events, using econometric models and time series analysis to understand price dynamics. Addressing the lack of specific research on Bitcoin's fair market value during halving events, the study shed light on the influence of halving events on Bitcoin's price fluctuations, considering other market dynamics. Furthermore, it explored additional factors affecting Bitcoin's valuation and employed predictive modeling to forecast the consequences of future halving events, providing valuable insights for investors, researchers, and policymakers in anticipating market behavior following such events. In summary, the paper contributed to the field by focusing on the impact of halving events on Bitcoin's fair market value and using rigorous methodologies to understand its price behavior.

Kroll et al. [11] utilised predictive modeling to forecast the future trends of Bitcoin mining activity. By analyzing historical data and considering factors such as changes in block rewards and mining difficulty, the researchers developed predictive models to anticipate the potential impact on the Bitcoin mining ecosystem. These models aimed to project how mining activity might have evolved in response to varying market conditions and technological advancements. Through the predictive modeling approach, the paper sought to provide insights into potential scenarios related to Bitcoin mining. This allowed researchers and stakeholders to understand better how the mining landscape could have unfolded, thus informing strategic decision-making and policy considerations in the rapidly evolving cryptocurrency ecosystem.

Wang et al. [12] focused on measuring and analyzing the Bitcoin network from the perspective of mining pools. The paper specifically examined the activities of mining pools in the Bitcoin network. Mining pools involve multiple miners collaborating to generate blocks and distribute rewards. This paper places particular emphasis on studying the operations of these mining pools. In particular, the paper investigated the changes in mining activities concerning Bitcoin's halving events. Halving events involved reducing the block rewards for miners, which could impact their earnings and mining difficulty. The study analysed the effects of these halving events on mining pool activities and the network as a whole, exploring block creation frequency, changes in mining participation, and other relevant factors. By approaching Bitcoin's network measurement and analysis from the perspective of mining pools, the paper aimed to provide valuable insights into Bitcoin's mining activities. Through the examination of mining pool behaviors and network dynamics, it contributed to evaluating and understanding the robustness and decentralization of the Bitcoin ecosystem.

Fantazzini et al. [13] investigated the impact of Bitcoin's mining hashrate on its price. The study analysed how the hashrate, representing the computational work in mining, influenced the cryptocurrency's value, emphasizing its significance for network security and mining profitability. Utilizing statistical methods and time series analysis, the research explored the correlation between hashrate and Bitcoin's price fluctuations to understand their interplay. The study found that the hashrate had a positive impact on Bitcoin's price, indicating that an increase in mining hashrate corresponded to higher cryptocurrency valuations. However, the relationship between hashrate and price was not found to be linear, suggesting that other factors may also influence Bitcoin's price dynamics.

Jireh et al. [3] investigated the price volatility trends of Bitcoin from the perspective of its halving events. The paper focused on the price volatility during the halving cycles of Bitcoin. Halving events occurred when the block rewards for Bitcoin miners were reduced, and the study explored the impact of these events on Bitcoin's price. The paper utilised the MSGARCH (Multivariate Singular Spectrum Generalised Autoregressive Conditional Heteroskedasticity) model to analyse Bitcoin's price volatility. By employing the MSGARCH model, the paper aimed to examine the volatility patterns of Bitcoin during its halving cycles and investigate how these events influenced the price volatility of Bitcoin. The study sought to provide valuable insights into the effect of halving events on the price fluctuations of Bitcoin.

Informed by the findings of the literature review [2, 3, 11–15], existing research has delved into various facets of Bitcoin halving events. However, a notable limitation in these studies is the predominant focus on analyzing the events, often neglecting crucial aspects such as predicting and preparing for future halving events, which assists miners in navigating the landscape after halving to maintain a robust net profit margin. However, to the best of our knowledge, there is a lack of research anticipating and preparing for upcoming events. Recognizing that historical analysis, coupled with predictions, plays a crucial role as a compass for those engaged in the mining business, addressing this gap becomes paramount. To overcome these limitations, this paper aims to expand the

knowledge in this field through research focused on predicting and preparing for future events.

IV. Data Analysis

This section presents a comprehensive analysis of key metrics surrounding Bitcoin's halving events, utilizing time series analysis to interpret patterns or trends in this data over time, providing a deeper understanding and insights into the dynamics. The analysis is partitioned into four distinct periods, each aligning with the occurrence of a halving event. Thus, Period 1 encompasses blocks 1 to 209,999, Period 2 covers blocks 210,000 to 419,999, Period 3 spans blocks 420,000 to 629,999, and Period 4 includes data from blocks between 630,000 and 796,629, as the subsequent halving event had not yet occurred at the time of this analysis. These events mark a significant milestone in Bitcoin's blockchain, where the block reward for miners is reduced by half approximately every 210,000 blocks. The delineation of these periods allows for a granular examination of how different phases of the halving events influence Bitcoin's transactional, economic, and market dynamics. We referenced Bitcoin's mainnet for block data (Transaction, Network Difficulty, and Reward) and utilised Yahoo Finance data for crypto price and trading volume data.

A. Key Metrics

This section covers a statistical analysis of key metrics data related to Bitcoin.

Metrics	**Period 1**	**Period 2**	**Period 3**	**Period 4**
SUM(TX)	9M	132M	388M	329M
AVG(TX)	44	628	1,846	1,977
AVG(D)	697K	41,742M	5,237G	26,795G
AVG(R)	50.04	25.18	13.28	6.60
AVG(F)	0.04	0.18	0.78	0.35
AVG(C)	5	336	5,787	30,756
AVG(V)	41,261	48,840	257,316	187,953

TABLE I: halving events Key Metrics

From the provided key metrics in Table I, several insightful observations can be made:

- Transaction Count (SUM(TX)): The consistent increase in total transaction count across periods signals the robust adoption and utilization of the Bitcoin network. This growth is attributable to factors such as heightened merchant acceptance, increased awareness, and implementation of scalability solutions like the Lightning Network. The transaction count experienced a significant increase, with a growth rate of approximately 4,211% from Period 1 to Period 3.
- Average Transactions per Block (AVG(TX)): The substantial surge in average transactions per block signifies heightened network activity and efficient block space utilization. Factors influencing this surge include adopting Segregated Witness (SegWit) and optimising transaction batching strategies. The average transactions per block rise significantly, with a growth rate of approximately 4,095% from Period 1 to Period 3.
- Average Network Difficulty (AVG(D)): The exponential growth in network difficulty underscores escalating competition among miners. This surge is linked to the proliferation of advanced mining hardware, improved mining pool efficiency, and miners' pursuit of higher profitability. Network difficulty experiences substantial growth, with an increase of approximately 3,714,848% from Period 1 to Period 4.
- Average Block Reward (AVG(R)): The consistent reduction in average block reward aligns with Subsidy halving events. This reduction reflects the protocol's design to emulate scarcity, ensuring a controlled and predictable supply schedule. The average block reward diminishes progressively, with a reduction of approximately 87% from Period 1 to Period 4.
- Average Transaction Fees (AVG(F)): Fluctuations in average transaction fees highlight dynamic fee market dynamics, with a notable rise in Period 3. Increased fees in Period 3 may be attributed to heightened demand, network congestion, and user willingness to pay for faster confirmations. Average transaction fees fluctuate, with an increase of approximately 1,850% from Period 1 to Period 3.
- Average Cryptocurrency Price (AVG(C)): Significant appreciation in average cryptocurrency price, particularly from Period 1 to Period 3. This upward trend suggests increasing investor interest and speculative demand, influenced by macroeconomic factors, institutional adoption, and media coverage. The Average cryptocurrency price increased substantially, with a growth rate of approximately 11,260%
- Average Trading Volume Trends: Variations in average trading volume, with a substantial increase in Period 3. Heightened trading activity during Period 3 indicates increased market engagement, possibly influenced by the third halving event. Average trading volume experiences variations, with an increase of approximately 361% from Period 2 to Period 3.

The Bitcoin ecosystem's consistent growth reflects its maturation over time, attributed to the adoption of scaling solutions and improved infrastructure. This evolution enhances the network's capacity to handle increased transaction volumes. The declining block rewards due to halving events encourage miners to rely more on transaction fees, as evident in Period 3's fee market dynamics.

The correlation between rising cryptocurrency prices and post-halving periods highlights the significance of price appreciation in sustaining miner profitability amid reduced block rewards. This phenomenon results from a combination of scarcity, growing demand, and an expanding user base, creating a self-reinforcing cycle where higher prices incentivise mining activity.

In conclusion, the observed trends signify a complex interplay of technological, economic, and market factors shaping the Bitcoin network's evolution. Despite diminishing block rewards, the ecosystem's continued growth underscores its

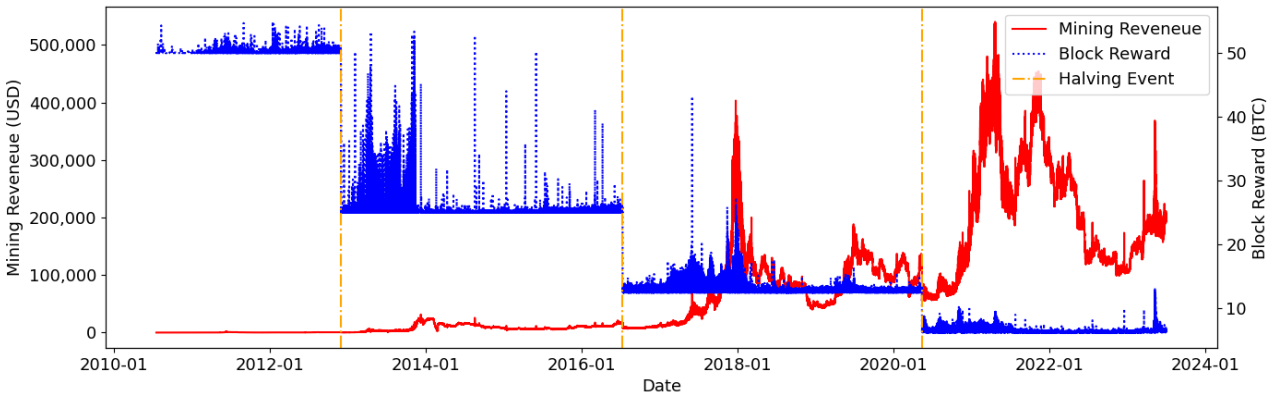

Fig. 3. Bitcoin Block Reward and Incentive Trend

resilience and adaptability to changing conditions.

B. Mining Revenue Variation

The absolute Bitcoin Subsidy awarded to miners has undergone a reduction of fifty percent on three separate occasions. Nevertheless, as illustrated in Figure 3, a conspicuous trend emerges, revealing that the adequate compensation for miners, denoted as the Mining Incentive and calculated by the multiplication of Block Reward and Crypto Price, exhibited a noteworthy surge after the second halving event in 2016. Notably, this surge in Mining Incentives surpassed the magnitude observed during the second halving event.

C. Transaction Fees Variation

During the halving events in November 2012, July 2016, and May 2020, a discernible escalation in transaction volume became evident. This surge in activity corresponded with a notable elevation in total transaction fees, as graphically illustrated in Figure 4. This phenomenon underscores the amplified significance of transaction fees stemming from the curtailed issuance of newly mined bitcoins. The subsequent analysis of the provided dataset offers the following insights.

- Changes in Transaction Count and Fees: A comprehensive examination of the dataset reveals a consistent and conspicuous upward trajectory in both transaction count and associated fees across the temporal spectrum. A particularly noteworthy surge is evident after May 2020, a development linked to the augmented valuation of Bitcoin and the concomitant escalation in user engagement.
- Average Fee per Transaction: After each halving event, a substantial surge in the average fee per transaction manifests. This surge remains consistently ascendant beyond 2021, underscoring an enduring trend towards elevated transaction fees as a mechanism for incentivizing network participants.
- Yearly Trends: An annual dissection of the data highlights persistent upward trajectories in both transaction count and fees. Significantly, the years 2022 and 2023 stand out due to pronounced fluctuations, plausibly attributable to the inherent volatility of the cryptocurrency market, exerting an influence on user conduct and transactional activity.
- Fee-Price Relationship: Noteworthy is the apparent positive correlation observed between transaction fees and the market price of Bitcoin. As the value of Bitcoin appreciates, users may exhibit an increased willingness to allocate higher fees, ensuring expedited and reliable transaction processing.

In summary, the analysis underscores the significant ramifications of halving events on transactional dynamics, emphasizing the pronounced role of transaction fees in the context of reduced newly minted bitcoins. The numerical investigation offers valuable insights into the evolving trends in transactional behaviors and fee structures, thereby contributing to a more comprehensive understanding of the observed phenomenon.

D. Crypto Price and Trading Volume Fluctuations

We examined the behavior of cryptocurrency prices and trading volume from [16] in relation to halving events as depicted in Figure 5.

- Trading Volume and Price Uptrend (July 2016 halving): Bitcoin's price witnessed an upward trend, accompanied by increased trading volume. This aligns with the notion that the scarcity-induced price increase incentivised greater trading activity.
- Price Rally and Volatile Trading Volume (May 2020 halving): The halving led to a price rally in Bitcoin. However, the trading volume showed a distinct fluctuation pattern, alternating between rises and declines. This could be attributed to the maturing Bitcoin market and the involvement of more participants, resulting in increased market volatility. The oscillating trading volume alongside the price surge indicates that market participants' strategies and overall market dynamics played a role.

Halving events influence the average trading volume, with Period 2 displaying a modest increment and Period 3 witnessing a notable upsurge. This suggests that halving events may stimulate increased trading engagement and heightened market

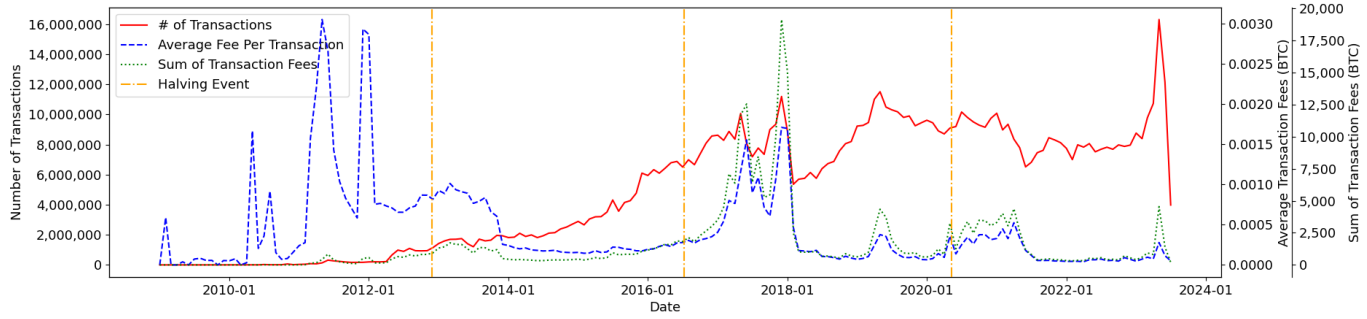

Fig. 4. Monthly Transaction Fees Trend

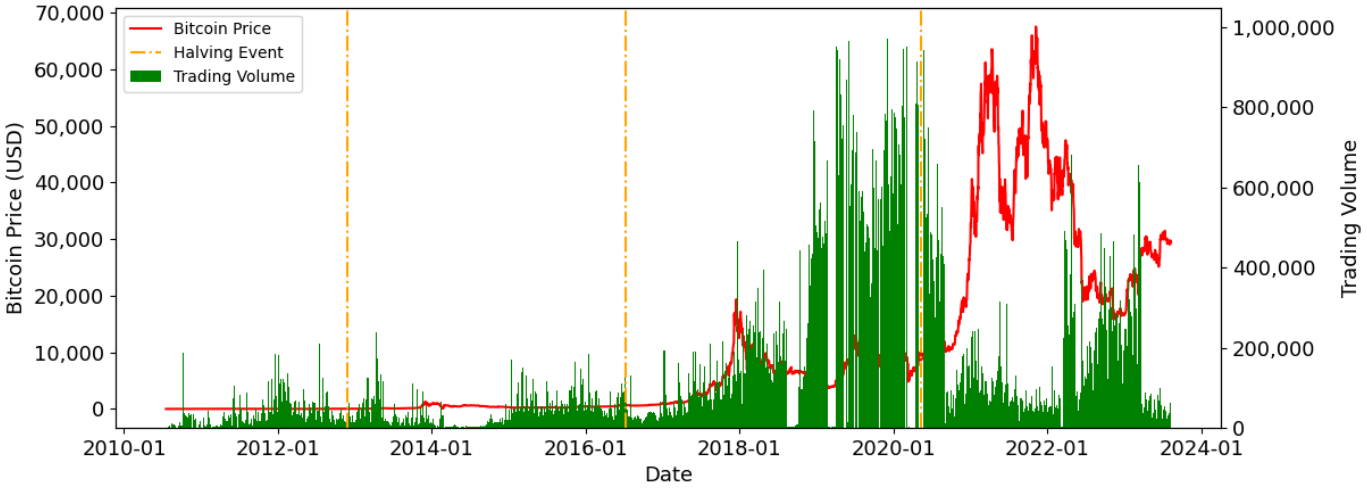

Fig. 5. Crypto Price and Trading Volume Trend

interest in Bitcoin, possibly influenced by shifts in supply dynamics and prevailing market sentiment. Notably, in Period 4, there is a decrease in average trading volume compared to the active Period 3, signalling a potential return to normal trading activity levels. The average trading volume gauges the market's responsiveness to halving events, capturing variations in trading activity and anticipating shifts in market dynamics. Empirical evidence indicates that halving events significantly impact trading volume, enhancing our understanding of Bitcoin's valuation and market behavior.

In summary, the analysis of key metrics reveals the maturation of the Bitcoin ecosystem, marked by consistent growth and adaptability. Scaling solutions and improved infrastructure bolster the network's capacity to handle increasing transaction volumes. The correlation between cryptocurrency prices and post-halving periods underscores the vital role of price appreciation in sustaining miner profitability amid diminishing block rewards. This self-reinforcing cycle, driven by scarcity, demand, and an expanding user base, contributes to the enduring resilience of Bitcoin.

V. Discussions

This section explores the post-halving event landscape, building upon the data analysis presented in the previous section. It delves into the prospective outlook on key metrics of mining revenue based on historical patterns and addresses strategic considerations for navigating the environment of decreasing subsidies.

A. Revenue Impact Metrics Outlook

As Bitcoin's halving events consistently reduce block rewards, miners face challenges in maintaining previous revenue levels. The upcoming 2024 halving event, halving the subsidy from 6.25 BTC to 3.125 BTC, necessitates discussing the values that Bitcoin price, network difficulty, and transaction fees (which greatly impact mining revenue) should attain to sustain miner income.

Metrics	**Current**	**ARIMA**	**Linear Regression**	**Random Forest**
BTC Price (USD)	37,156	68,088	57,790	22,436
Subsidy (BTC)	6.25	3.125	3.125	3.125
TX Fees (BTC)	0.92	0.67	0.69	0.44
Revenue (USD)	266,409	258,394	220,469	79,984
Change (%)	-	-2.91%	-17.34%	-69.95%

TABLE II: Mining Revenue Expectation (per block)

Table II presents the current/predicted revenue per block by considering Bitcoin price, subsidy, and transaction fee. The "Current" column encapsulates data values recorded as of November 12, 2023. We employ three distinct models to analyse time series data in the context of Bitcoin's market trends. The "Change" column represents the percentage change of Revenue compared to the Current value. We employ forecasting models, ARIMA, Linear Regression, and Random Forest to analyse Bitcoin market trends. Each model serves a unique purpose, and their selection is based on their ability to capture time-dependent patterns.

The AutoRegressive Integrated Moving Average (ARIMA) model, known for its capability to capture time-dependent patterns, is utilised. The ARIMA model leverages historical Bitcoin prices to predict future values. For this analysis, we set the ARIMA model parameters as follows: p (Autoregressive order) is 1, d (Integrated order) is 1, and q (Moving Average order) is 1.

In addition to ARIMA, we employ Linear Regression and Random Forest models to explore both linear and non-linear relationships within the dataset. The Linear Regression model includes the following parameters: `fit_intercept=True`, which calculates the intercept for this model; `copy_X=True`, indicating that X will be copied, otherwise it may be overwritten; and the parameter `n_jobs=None`, specifying the number of jobs to use for the computation, with None indicating 1 unless in a joblib.parallel_backend context. The Random Forest model is configured with the following parameters: `n_estimators=100` (the number of trees in the forest), `min_samples_split=2` (the minimum number of samples required to split an internal node), `min_samples_leaf=1` (the minimum number of samples required to be at a leaf node), and `max_features=1.0` (the number of features to consider when looking for the best split; 1.0 means all features are considered).

The results of our analysis indicate diverse approaches to time series analysis, with each model offering unique insights into Bitcoin market dynamics, as follows.

- Bitcoin Price (BTC Price): The current Bitcoin price is 37,156 USD, notably lower than the ARIMA model's prediction of 68,088 USD. Linear Regression and Random Forest models present more conservative estimates at 57,790 USD and 22,436 USD, respectively. The ARIMA and Linear Regression models forecast a significant surge in Bitcoin price, while the Random Forest model deviates with a considerably lower projection.
- Transaction Fees (TX Fees): Current transaction fees are 0.92 BTC, with models predicting different futures. ARIMA anticipates a decrease to 0.67 BTC, Linear Regression expects a slight increase to 0.69 BTC, and the Random Forest model suggests a more substantial drop to 0.44 BTC.
- Revenue: The current revenue per block is 266,409 USD, expected to decline. ARIMA's forecast of 258,394 USD (-2.91%) aligns closely with the expected decrease, while Linear Regression provides a more optimistic projection of 220,469 USD (-17.34%). The Random Forest model, however, diverges significantly with a notably lower estimate of 79,984 USD (-69.95%). The Random Forest model significantly deviates from other predictions; however, due to its ability to capture finer variations that other models might miss, it demonstrates superior performance across most metrics.

As indicated in Table II, mining revenue is anticipated to range from 79,984 to 258,394 USD. The cryptocurrency price needs to range from 69,832 to 74,729 USD to sustain revenue levels comparable to the previous state. However, it is crucial to consider the expected increase in Network Difficulty, leading to a proportional rise in mining energy costs. Taking this into account, miners should not only focus on sustaining revenue but also on optimising energy costs to maintain a healthy net profit margin. The following section will explore strategies for maintaining revenue levels while optimising energy costs, providing a more detailed analysis of this critical aspect.

Table III presents evaluation metrics for predicted models of Bitcoin Price and Transaction Fees. The following metrics were utilised to assess prediction performance: MAE (Mean Absolute Error), MSE (Mean Squared Error), RMSE (Root Mean Squared Error), and R2 (R-squared). These metrics offer insights into overall accuracy, sensitivity to errors, spread of deviations, and explanatory power, respectively. The statistical data of Bitcoin price and transaction fees analysed in the previous section were used for fitting models, assuming that the data from the previous halving event period will continue to have an impact in the future.

	Metrics	**ARIMA**	**Linear Regression**	**Random Forest**
Bitcoin Price	MAE	0.0378	0.1113	0.0129
	MSE	0.0043	0.0372	0.0005
	RMSE	0.0655	0.1928	0.0223
	R2	0.9776	0.8058	**0.9974**
Transaction Fees	MAE	0.2890	0.4056	0.0562
	MSE	0.1787	0.2545	0.0095
	RMSE	0.4228	0.5045	0.0973
	R2	-0.0092	-0.4373	**0.9465**

TABLE III: Prediction Evaluation Metrics

For Bitcoin Price prediction, The ARIMA model achieved a low MAE of 0.0378, indicating small average prediction errors, and demonstrated high accuracy with an R2 value of 0.9776, explaining 97.76% of the variance in Bitcoin prices. In contrast, the Linear Regression model had a higher MAE of 0.1113, suggesting larger prediction errors, and explained 80.58% of the variance in Bitcoin prices, slightly lower than ARIMA. The Random Forest model outperformed with the lowest MAE of 0.0129 and the highest R2 value of 0.9974, indicating exceptional accuracy and explanatory power.

In terms of Transaction Fee prediction, The ARIMA model exhibited a relatively high MAE of 0.2890, indicating notable prediction deviations. In contrast, the Linear Regression model had a higher MAE of 0.4056 and a negative R2 value of -

0.4373, suggesting poor performance in explaining variance. In contrast, the Random Forest model demonstrated superior performance with the lowest MAE of 0.0562 and the highest R2 value of 0.9465, indicating accurate predictions and strong explanatory power.

These predictions are based on historical data, and actual future data may be influenced by variables such as the evolution of equipment, macro trends, or unforeseen events. Therefore, while these predictions can help adjust existing strategies to respond to current trends and environmental changes, they should be approached with caution due to the potential impact of unpredictable factors. Historically, a positive correlation has been observed between Bitcoin price and halving events.

B. Future Observations

As the anticipated halving event in April 2024 approaches, a thorough assessment of potential implications for miners and the broader Bitcoin ecosystem becomes imperative. Drawing insights from past halving events provides valuable perspectives on how the upcoming event might impact miner business models, network dynamics, transaction fees, cryptocurrency prices, and overall mining profitability.

1) Miner Business Model: The consistent reduction in block rewards during halving events challenges the conventional business model of miners relying on subsidies. As illustrated in Figure 3, effective compensation for miners has shown significant surges following past halving events. This trend indicates that miners have adeptly adapted to subsidy reductions by leveraging the increased value of Bitcoin. To prepare for the 2024 halving event, miners must continually optimise their operations. This may involve:

- Efficiency Improvements: Investing in the latest mining hardware and technologies to enhance efficiency and hash rates, maximizing the chances of successfully mining blocks.
- Elastic Mining Model: Developing elastic/dynamic mining profit management for energy-efficient blockchain mining is essential. This approach allows systematic analysis, considering various variables influencing mining operations, aiding miners in making informed decisions for long-term sustainability and profitability.

2) Energy Cost and Sustainability: The environmental impact of Bitcoin mining has become a focal point of discussions and regulatory considerations. As the industry faces increased scrutiny, miners must proactively address sustainability concerns. Strategies for enhancing sustainability include the following.

- Energy Cost Optimisation: Miners can strategically transition to or increase their reliance on renewable energy sources, aligning with global sustainability goals. This not only contributes to environmental responsibility but also serves to mitigate potential regulatory risks associated with carbon-intensive mining. To further enhance energy cost optimisation, miners may consider diversifying energy sources, including renewables, dynamic wholesale energy, surplus energy utilization, and incorporating battery storage solutions for improved efficiency in blockchain mining operations.
- Optimising Mining Equipment Deployment: To efficiently manage mining operations, including ASICs, GPUs, and rigs, a thorough analysis of each equipment's potential revenue during the creation of a single block is essential. This approach ensures the strategic allocation of resources to maximise efficiency and returns in mining activities.

Balancing economic incentives, technological advancements, and sustainability is key to ensuring the continued growth and resilience of the Bitcoin network. The ability to adapt to changing conditions, implement innovative solutions, and foster a collaborative ecosystem will be pivotal in navigating the evolving landscape of cryptocurrency mining. As the industry matures, strategic decisions made in preparation for the 2024 halving event will shape the future trajectory of Bitcoin and its role in the broader financial landscape. Many future strategies discussed above will require significant attention and research from academia and the industry. It is anticipated that such research efforts will play a crucial role in ensuring the continued growth and resilience of the Bitcoin network.

VI. Conclusion and Future Works

Our investigation into Bitcoin's historical halving events reveals a maturing ecosystem, evidenced by periods around halving events characterised by growth in transaction count, network difficulty, and market activity. Miners adeptly navigate subsidy reductions, capitalizing on the increasing value of Bitcoin. Strategic preparations are crucial for the anticipated 2024 halving events, where miners should focus on efficiency, revenue diversification, and sustainable energy.

The 2024 halving event in Bitcoin, reducing the block reward from 6.25 BTC to 3.125 BTC, poses challenges for miners' revenue. Projections suggest a decline in revenue per block, ranging from -2.91% (ARIMA) to -69.95% (Random Forest). Sustaining comparable revenue levels would require Bitcoin's price to increase to a minimum of 69,832 USD. Miners should prioritise strategies to optimise energy costs in this evolving landscape.

Future research will explore advanced optimisation models for energy-efficient blockchain mining, considering factors like energy costs, equipment deployment strategies, and renewable energy utilization. Refining mathematical frameworks could provide miners with comprehensive tools for sustainable decision-making in the evolving landscape of cryptocurrency mining.

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