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Research article

Renewable energy and cryptocurrency: A dual approach to economic viability and environmental sustainability

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ABSTRACT

One of the foremost challenges facing Bitcoin, as the most valuable cryptocurrency operating on a proof-of-work mechanism, is its substantial energy consumption and environmental impact. With the expansion of the Bitcoin market, mining has surged in popularity, particularly in countries where energy and monetary costs are comparatively low. This study aims to assess the impact of utilizing renewable energy from a photovoltaic system for Bitcoin mining, simulating a solar power plant with a 50.91-MW capacity alongside a corresponding Bitcoin mining operation in the United Arab Emirates. Economic evaluations were conducted using comprehensive, historically archived data to ensure results that closely mirror real-world scenarios. Additionally, for a more nuanced comparison, an economic assessment of selling the power plant's electricity to the grid was also performed, with the findings juxtaposed. The outcomes indicate that initiating such a system at the start of 2020 with an investment of approximately $42 million could recoup its costs in about 3.5 years. In contrast, selling electricity to the grid would extend the power plant's return on investment period to 8.1 years. Furthermore, the environmental evaluation revealed that adopting renewable solar energy for mining could avert the emission of around 50,000 tons of CO_2 annually.

Nomenclature

		Abbreviations		Symbol and meaning	
GlobHor	Horizontal global irradiation (kWh/m^2)	PV	Photovoltaic	V	Voltage
DiffHor	Horizontal diffuse irradiation (kWh/m^2)	PR	Performance Ratio	A	Ampere
T_Amb	Monthly average ambient temperature (∘C)	AC	Alternative Current	Ah	Ampere hour
GlobInc	Global radiation on tilted PV array (kWh/m^2)	DC	Direct Current	°C	degree Celsius
GlobEff	Effective global radiation (kWh/m^2)	POW	Proof Of Work	g	gram
EArray	Energy generated at the output of the PV array (MWh)	POS	Proof Of Stake	m^2	meter square
E_Grid	Energy injected into the grid (MWh)	ROI	Return on Investment	kVA	Kilo-Volt-Ampere
V_{oc}	Open circuit voltage (V)	IRR	Internal Rate of Return	kW	kilo Watt
V_{mp}	Maximum power point voltage (V)	NPV	Net Present Value	kWh	kilo-Watt-hour
I_{sc}	Short circuit current (A)	LCOE	Levelized Cost of Energy	MWh	Mega-Watt-hour
I_{mp}	Maximum power point current (A)	PUE	Power Usage Effectiveness	GWh	Giga-Watt-hour
Tol	Tolerance (−/+%)			Th	Terahash

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(*continued*)

Eff	Efficiency (%)	s	second
Si-mono	Monocrystalline silicon		

1. Introduction

Blockchain technology first gained public attention with the launch of Bitcoin in 2009, marking its debut as a decentralized financial application [1]. Today, Bitcoin's market valuation exceeds 1 trillion dollars, and over the past decade, blockchain technology has evolved significantly. This evolution has expanded beyond Bitcoin to include platforms like Ethereum, which enable decentralized applications with remarkable adaptability [2]. As blockchain has developed, researchers and experts have increasingly recognized its potential to revolutionize sectors beyond digital currencies [3,4].

At its core, blockchain technology facilitates secure, intermediary-free transactions, appealing to individuals, industries, and public sectors alike [5–7]. The validation process for transactions on the Bitcoin blockchain operates through a proof-of-work mechanism, which requires energy-intensive hardware. This process converts valuable energy, such as electricity, into less valuable forms like heat [8–10]. As a result, Bitcoin's high energy consumption has raised significant concerns about its environmental sustainability, with critics citing it as a problematic aspect of blockchain technology [11,12].

The growing urgency of climate change, characterized by increasing global temperatures, has prompted a reassessment of energy consumption policies worldwide [13]. Energy use from activities like Bitcoin mining contributes to carbon emissions, exacerbating environmental damage [14]. Although less energy-intensive blockchain mechanisms have emerged, national policies are increasingly targeting technologies that consume high levels of energy [15–17]. Integrating renewable energy sources, such as solar power, into these systems could allow for more environmentally responsible and sustainable operations [18].

Among renewable energy sources, solar power stands out, particularly in regions like the Middle East, due to their high levels of sunlight and predominantly clear skies [11]. Key factors in evaluating the feasibility of solar energy production include solar irradiance, climate conditions, geographical features, economic considerations, and local regulations [19–21]. Countries like the United Arab Emirates and Iran hold significant potential for large-scale solar power installations [11], with advantages such as low electricity costs, efficient transmission capabilities, and high solar energy contributions [22].

Photovoltaic (PV) systems, one of the most widely used technologies for capturing solar energy, play a pivotal role in mitigating global warming and addressing climate change [23,24]. PV systems offer several advantages: they convert sunlight directly into electricity without producing harmful emissions, significantly reducing greenhouse gases like CO_2. While the manufacturing and installation processes of PV systems involve some initial emissions, these are generally lower than those associated with other renewable energy sources like wind or hydroelectric power. Additionally, PV systems are highly scalable, making them suitable for a wide range of applications, from small residential setups to large solar farms. This adaptability gives PV an edge over other renewables like hydroelectric power, which is geographically restricted, and wind energy, which depends on specific conditions for optimal performance. Another key benefit of PV technology is its rapidly decreasing cost; the price of solar panels has plummeted in the past decade, making solar energy increasingly competitive with conventional energy sources [25].

Given the increasing scrutiny of Bitcoin's energy consumption and environmental impact, the integration of renewable energy sources, such as photovoltaic systems, presents a promising solution. This study explores the feasibility of using solar energy to power Bitcoin mining operations, specifically in regions with high solar potential like the United Arab Emirates. By comparing the economic and environmental outcomes of using solar power for mining versus selling electricity to the grid, this research aims to provide a dual perspective on economic viability and environmental sustainability. The following section delves into the existing literature on blockchain energy consumption, renewable energy integration, and the environmental implications of both, providing a foundation for this analysis.

2. Literature review

2.1. Bitcoin Mining's environmental and energy impacts

Bitcoin's energy consumption has been a major focus of substantial research [8,15,26–28]. In 2018, Christian Stoll et al. utilized blockchain data, insights from hardware manufacturers' IPO filings, and mining pool compositions to estimate Bitcoin's global energy consumption at 45.8 TWh [8]. Similarly, Alex de Vries applied economic modeling that same year, estimating Bitcoin's lower bound energy consumption at 2.55 GW, with an upper range of 7.67 GW, comparable to the energy usage of countries like Ireland (3.1 GW) and Austria (8.2 GW) [26].

In another 2018 study, Max J. Krause et al. compared the energy consumption per US dollar produced across various blockchains, finding that mining one dollar's worth of Bitcoin required 17 MJ of energy—more than the energy costs of mining materials like copper, gold, platinum, and rare earth oxides [28]. By 2020, Bitcoin's energy consumption was approaching levels equivalent to those of countries like the Netherlands and Argentina [29], raising concerns about its environmental sustainability [11,12].

Numerous studies have translated Bitcoin's energy consumption into environmental impacts [8,30–40]. Christian Stoll et al. estimated Bitcoin's carbon footprint in 2018 to be around 22 $MtCO_2$, akin to the annual emissions of countries like Jordan or Sri Lanka [8]. In 2019, Alex de Vries evaluated the use of renewable energy in Bitcoin mining, estimating that each Bitcoin transaction in 2018 produced between 233.4 and 363.5 kg of CO_2, far exceeding the 0.4 g of CO_2 produced by a Visa transaction [30,41]. In contrast, a 2017 study projected Bitcoin's emissions could reach 69 $MtCO_2$ annually, potentially contributing to a 2-degree Celsius global temperature rise [42].

Additionally, Andrew L. et al. (2018) assessed the health and climate damages caused by Bitcoin mining in the U.S. and China, estimating costs at 0.49 and 0.37 dollars per Bitcoin generated, respectively [31]. Spyros F. (2018) reported that the combined energy consumption of Bitcoin and Ethereum, representing approximately 88 % of the cryptocurrency market's value, was around 47 TWh, just below Greece's total energy consumption of 57 TWh [36]. Houy (2017) also estimated Bitcoin's greenhouse gas emissions to range from 2.9 $MtCO_2$ to 35.1 $MtCO_2$, with 2017 emissions calculated at 15.5 $MtCO_2$ [43]. These findings underscore the sustainability concerns surrounding Bitcoin, which could influence its broader adoption in light of climate change discussions [2].

In a recent 2024 study, Bâra et al. explored the relationship between Bitcoin's energy consumption and transaction volumes over a three-year period, utilizing advanced meta-model and SQL analytics to forecast Bitcoin prices. This study underscores the complex interplay between Bitcoin's energy usage and its environmental impact, particularly regarding carbon emissions [44].

While much of the existing literature has focused on Bitcoin's price prediction, market volatility, and financial risk management, there remains a significant gap in addressing the environmental and economic implications of mining operations. Our research fills this gap by examining the integration of renewable energy, particularly photovoltaic (PV) systems, into Bitcoin mining, considering both economic and environmental perspectives. Bâra et al. (2024) [44] provided valuable insights into Bitcoin's energy consumption and its environmental footprint through a meta-model with 15 variables. However, their work mainly emphasized price prediction and market trends, leaving room for further exploration of practical, energy-efficient mining solutions. In contrast, our study goes beyond energy consumption analysis by proposing a renewable energy solution that integrates PV systems into Bitcoin mining operations.

In the domain of price prediction and volatility, Baroiu (2023) [45] leveraged deep learning techniques by combining on-chain data with Twitter sentiment, outperforming traditional models in accuracy. Similarly, Oprea (2024) [46] analyzed Bitcoin's price evolution and volatility from 2014 to 2023 using econometric models like EGARCH, which, while offering valuable insights, failed to address the environmental consequences of Bitcoin mining, such as CO_2 emissions and energy consumption.

Further reinforcing this focus on market dynamics, Bâra et al. (2024) [47] employed advanced GARCH modeling to study the volatility relationships between Bitcoin, traditional financial markets, and commodities like Brent crude oil. This research illuminated how economic conditions and market sentiment influence Bitcoin's volatility but, like many others, did not address Bitcoin's environmental impact.

Recent studies have also underscored the need for deeper investigations into the sustainability challenges of Bitcoin mining. Bâra et al. (2024) [48] found a weak correlation between academic research outputs and Bitcoin price movements, emphasizing the lack of attention to mining's energy demands and environmental impacts. Our study contributes to this critical discussion by evaluating the economic feasibility of using solar energy for Bitcoin mining, presenting a robust framework that integrates real-time market dynamics and environmental considerations.

Further advancements in Bitcoin price prediction have been made, as demonstrated by Bâra et al. (2024) [49], who used ensemble learning methods with feature engineering, employing multiple classifiers and regressors to improve forecast accuracy. Despite these improvements, the focus remains on market predictions rather than on the economic and environmental implications of mining operations.

Finally, innovative optimization approaches for Bitcoin mining have emerged, such as the Quantum-inspired Multi-objective Optimization Algorithm (QMOA) presented by Oprea et al. (2024) [50]. This algorithm optimizes Bitcoin trading profits while minimizing energy costs, although its primary focus remains on profit maximization rather than addressing the broader energy and environmental challenges.

2.2. *Integration of renewable energy into Bitcoin mining*

A growing body of research has explored the potential of using renewable energy sources in cryptocurrency mining systems, particularly as concerns about the environmental impact of mining increase [51–55]. For instance, Nikzad et al. examined the economic efficiency of a grid-connected rooftop photovoltaic (PV) system for Ethereum mining in Iran, considering legal constraints [53]. However, with Ethereum's transition from Proof of Work (PoW) to Proof of Stake (PoS) following its 'Merge' update, such mining setups are no longer applicable [56]. In contrast, Serhat et al. (2022) investigated the feasibility of using nuclear energy for Bitcoin mining, highlighting its advantages, such as zero greenhouse gas emissions and continuous energy generation, making it a highly viable option for sustainable Bitcoin mining [52]. Gundaboina et al. explored the effects of overclocking and undervolting on energy consumption and hash rate during Dogecoin mining using solar energy, suggesting that improved hardware configurations could reduce electronic waste and enhance sustainability in future mining operations [57]. Malfuzi et al. analyzed the economic viability of using a Solid Oxide Fuel Cell (SOFC) powered by renewable energy for Bitcoin mining, incorporating thermodynamic modeling to assess fuel needs under different scenarios depending on Bitcoin's price and mining difficulty [51].

Recent studies have taken further strides in integrating renewable energy into cryptocurrency mining, advancing both the economic and environmental dimensions. One emerging concept is the use of cryptocurrency mining as a virtual energy storage solution. Hajiaghapour-Moghimi (2024) [58] introduced Cryptocurrency Energy Storage Systems (CESSs), which act as virtual storage for microgrids, significantly reducing operational costs and nearly eliminating renewable energy curtailment. Although this innovation focuses on microgrids, our research builds on this by conducting a comprehensive economic analysis based on historical price data from a large-scale PV-powered Bitcoin mining system. This approach offers a more realistic evaluation of both financial and environmental impacts, specifically in the context of renewable energy integration within mining operations in a particular geographic setting.

Innovative approaches have also been proposed to incentivize the adoption of renewable energy in cryptocurrency mining. For example, Saquib (2023) [59] introduced GreenCoin, a cryptocurrency designed to be energy-efficient by favoring nodes located in regions rich in renewable energy. Although GreenCoin addresses energy efficiency through modifications to the consensus mechanism, it does not sufficiently address the economic benefits of renewable energy utilization. In contrast, our study offers a detailed economic analysis of a PV-powered Bitcoin mining operation, illustrating both the financial advantages and significant carbon emission reductions. This multifaceted approach enhances the understanding of renewable energy integration in cryptocurrency mining, providing insights that go beyond energy-aware mining protocols.

Vicente (2023) [60] developed a decision-support tool for assessing the feasibility of cryptocurrency mining as a revenue stream for renewable energy projects. While their findings suggest that mining can improve the financial performance of renewable investments, their model is limited to specific scenarios and primarily emphasizes photovoltaic systems. Our research expands on Vicente's work by conducting a thorough analysis of the renewable energy system itself, incorporating practical considerations such as geographical conditions and operational dynamics, particularly within the context of the UAE.

Several studies have also addressed the financial aspects of renewable energy-powered mining. Rorich (2023) [61] examined the use of solar energy for Bitcoin mining in South Africa, demonstrating the economic potential of directly connecting a solar system to mining rigs via a DC-DC link. However, the lack of battery storage in their model limits mining operations to daylight hours. In contrast, our study integrates energy swapping with the national grid, providing a continuous power supply and a more practical solution for large-scale mining operations that extend beyond solar production hours.

Table 1

Comparison of previous research on renewable energy integration in cryptocurrency mining.

Study	Energy Source	Economic Analysis	Environmental Impact	Key Innovations	Gaps Addressed by Our Study
Houy (2017) [43]	General energy mix	No	Estimated Bitcoin emissions (2.9–35.1 $MtCO_2$)	Energy and emission estimates	Did not analyze renewable energy or propose specific solutions for emission reduction.
Christian Stoll et al. (2018) [8]	General energy mix	No	Estimated Bitcoin's carbon footprint (22 $MtCO_2$)	Detailed energy consumption analysis	Lacked a renewable energy focus or practical solutions for emission reductions.
Alex de Vries (2018) [26]	General energy mix	Economic modeling of energy consumption	Carbon emissions per Bitcoin transaction	Global energy consumption estimates	Did not explore renewable energy integration or energy-efficient mining practices.
Max J. Krause et al. (2018) [28]	General energy mix	Comparison of energy consumption to other industries	No	Comparative energy consumption analysis	Lacked a focus on renewable energy and economic viability for mining operations.
Nikzad et al. (2022) [53]	Photovoltaic (PV)	Economic efficiency of PV systems for Ethereum mining	No	Grid-connected PV systems	Ethereum transitioned to PoS, making this study outdated for PoW mining like Bitcoin.
Serhat et al. (2022) [52]	Nuclear energy	No	Zero greenhouse gas emissions	Feasibility of nuclear energy for mining	Focused only on nuclear energy, not renewable energy integration like solar.
Gundaboina et al. (2022) [57]	Solar energy	No	E-waste reduction through hardware optimization	Overclocking/ undervolting for energy efficiency	Limited to hardware-level energy efficiency; did not assess large-scale renewable energy integration.
Liang (2022) [62]	Hydropower	Financial benefits of hydropower for Bitcoin mining	No	Hydropower benefits over fossil fuel systems	Focused on hydropower, not a comprehensive renewable energy approach.
Malfuzi et al. (2022) [51]	Solid Oxide Fuel Cell (SOFC)	Economic viability based on thermodynamic modeling	No	SOFC-powered mining	Did not consider other renewable sources like solar or explore practical large-scale solutions.
Saquib (2023) [59]	Renewable energy-rich regions	No	Energy efficiency in consensus mechanisms	GreenCoin as an energy-efficient cryptocurrency	Lacked detailed economic analysis of renewable energy integration into mining.
Vicente (2023) [60]	Photovoltaic (PV)	Feasibility of cryptocurrency mining as revenue for renewables	No	Decision-support tool for renewable projects	Focused only on specific renewable scenarios and lacked geographical or operational analysis.
Rorich (2023) [61]	Solar energy (South Africa)	Economic potential of direct solar to mining rigs	No	Direct solar-to-mining DC-DC link	Lacked battery storage or continuous power supply mechanisms.
Hajiaghapour-Moghimi (2024) [58]	Renewable energy for microgrids	Reduction in operational costs and renewable energy curtailment	No	Cryptocurrency Energy Storage Systems (CESSs)	Focused on microgrids, not large-scale PV systems or energy swapping mechanisms.
This Study (2024)	Photovoltaic (PV) + Grid Integration	Economic feasibility based on real-world price data	Life cycle emissions, e-waste, carbon reduction	Energy swapping, grid stability, practical PV integration	Comprehensive economic, environmental, and operational analysis with innovative energy swap mechanisms.

Liang (2022) [62] explored the financial benefits of using hydropower for Bitcoin mining in the United States, highlighting its advantages over fossil fuel-based systems. Although this study focused solely on hydropower, our research provides a broader economic evaluation that includes real-time market fluctuations. We demonstrate the superior performance of a combined PV and mining system, particularly in the UAE, where solar energy can offer both economic and environmental benefits. Our findings emphasize the importance of accounting for geographic and operational factors when integrating renewable energy into mining operations.

The environmental impact of cryptocurrency mining remains a pressing concern. Tomatsu (2023) [63] conducted a survey of Bitcoin's energy consumption, discussing the potential for renewable energy adoption. However, their study lacks detailed economic analysis. Our research addresses this gap by providing concrete data on potential CO_2 emission reductions achievable through solar-powered mining. Specifically, we demonstrate that a PV-powered Bitcoin mining system can significantly reduce carbon emissions over its lifespan while offering solid financial returns. This combination of economic and environmental analysis provides a more comprehensive understanding of the benefits of renewable energy integration in cryptocurrency mining.

2.3. Summary and comparison of recent studies

Our study offers a comprehensive and innovative approach to integrating renewable energy into cryptocurrency mining, particularly Bitcoin mining operations. Unlike previous research that often focused on isolated aspects such as energy consumption or price prediction, our work provides a holistic evaluation that combines detailed economic analysis, environmental impact assessments, and practical implementation considerations.

Key features of our research include.

1. **Economic Feasibility Analysis**: We employ a nuanced economic model based on extensive historical price data and real-world market conditions to assess the viability of installing a solar power plant for Bitcoin mining.
2. **Environmental Impact**: Our study goes beyond energy consumption to consider the full environmental footprint, including life cycle emissions (LCE) associated with producing solar panels and mining equipment, as well as the often-overlooked issue of electronic waste (e-waste) generated by Bitcoin mining.
3. **Energy Swap Mechanisms**: We introduce an innovative energy swapping strategy that eliminates the need for battery storage while contributing to grid stability. This approach addresses limitations of conventional energy storage systems in handling seasonal variations and mitigates supply and demand imbalances caused by mining rigs' energy consumption.
4. **Advanced Methodological Framework**: Our research utilizes PVsyst software for simulations, incorporating real-time historical data and meteorological inputs for more realistic assessments.
5. **Quantifiable Impact**: We demonstrate significant potential for carbon emission reductions, projecting the prevention of million tons over the plant life time.
6. **Policy Recommendations**: We advocate for comprehensive policies urging regulators to mandate the use of renewable energy for large-scale cryptocurrency mining operations.

Our work distinguishes itself from previous studies by addressing notable gaps in the literature, particularly in economic calculations, energy swap mechanisms, and comparisons of pollution generated by mining activities. As highlighted in Table 1 of our study, previous research on using renewable energy for mining has significant gaps in these areas. Our comprehensive approach fills these gaps and provides a more complete picture of the challenges and opportunities in this field.

By offering a holistic view that aligns economic efficiency with sustainability, our research provides valuable insights for both investors and policymakers in the cryptocurrency mining and renewable energy sectors.

In conclusion, our study contributes significantly to the rapidly evolving field of cryptocurrency mining and renewable energy integration. By combining rigorous economic analysis, environmental impact assessments, and practical system implementation considerations, we offer a more comprehensive evaluation of the challenges and opportunities in this domain, fostering more responsible practices in the cryptocurrency industry.

3. Methodology

In the pursuit of simulating and conducting an economic evaluation, the study period was set to commence at the beginning of 2020. This choice was predicated on the accessibility of requisite data pertinent to Bitcoin consumption and mining activities up to the present date, ensuring the accuracy of system performance assessment. The present simulation mandates prognosticating both mining and economic data, a task unfeasible over extended durations. The study aims, as delineated in the introduction section, revolve around the establishment of an optimized Bitcoin mining operation supported by a PV system to supply the mining required electricity in the United Arab Emirates. The mining system's design prioritized the utilization of devices that demonstrated the highest energy efficiency within the study's temporal scope, marked by the lowest energy consumption for a given hash rate output. Miner selection adhered to a criterion stipulating a minimum 90-day period post-launch, guided by data sourced from mining-related websites [64]. Miners released prior to 2021 were ranked according to energy efficiency.

The most efficient miners were identified as those produced by Bitmain, the leading manufacturer of new Bitcoin mining machines, boasting an alleged market share of 70 % [26,65]. Each of the top three miners demonstrated an energy consumption rate of 39.5 J per tera hash, as detailed in Table 2. Owing to the absence of precise pricing data for miners in 2020 and their subsequent obsolescence, prices were retrieved from online sales archives [66–68]. The selection process for the initial three miners on the list was conducted such that each miner accounted for one-third of the total power consumption. A further rationale for selecting three distinct miner types was to facilitate demand management as opposed to relying on a single miner model.

Subsequent to the selection phase, the study addressed the ancillary costs associated with establishing the mining system. An ancillary cost of $520 per miner was established, encompassing all facets of construction, equipment, and cooling mechanisms. This figure approximately constitutes a quarter of the cost of the most expensive miner. The Power Usage Effectiveness (PUE) for the system was set at 1.1, with the considered efficiency spectrum ranging from 1.01 (minimal wastage) to 1.25 (high wastage). The total count of miners, encompassing all three types, was determined to be 4000, underpinning an initial budget estimate of approximately 9 million $. Armed with this data, the system was designed to operate with an approximate power consumption of 9.3 MWp, translating to a daily electricity usage of around 200 MWh. Notably, this study did not incorporate costs related to miner shipping or ongoing monthly support. The encompassed costs were confined to purchase, installation, and initial setup expenditures.

For the economic analysis over the defined period, it is imperative to ascertain the Bitcoin mining output based on the system's hash rate. According to Carl et al., 2014 [69], the time required for mining a single block within the network can be calculated via Eq. (1):

$$T_m \approx \frac{HR}{ND \times 2^{32}} \tag{1}$$

T_m = Mining Time for One Block [s]
HR = Hash Rate [H/s]
ND = Network Difficulty.

Considering the network's constant block reward, the quantity of Bitcoin mined over a specified duration can be deduced using Eq. (2):

$$BTC_m = \frac{Tot.HR \times TP \times NRR}{ND \times 2^{32}} \tag{2}$$

BTC_m = Mined Bitcoin Amount.
Tot.HR = Total Network Hash Rate [H/s]
TP = Time Period.
NRR = Network Reward Rate.
ND = Network Difficulty.

With daily network difficulty data [70] and the system's daily hash rate calculation, the study accurately determined daily Bitcoin production figures.

The network reward rate, an anti-inflationary mechanism implemented by the network's developer, undergoes a halving every four years since its inception in 2008. At the time of this article, the reward stood at 6.25. Initially, in early 2020, this rate was 12.5, which subsequently halved on June 11, 2020. The next halving in 2024 is anticipated to reduce this rate to 3.125. The overarching goal is to mine the total cap of 21 million Bitcoins by 2120, with about 19 million already in circulation at the time of this writing.

For the economic evaluation, various temporal scenarios for the sale of the mined Bitcoins were considered. However, due to the inherent unpredictability of the digital currency market, formulating an optimal scenario for analysis was deemed unfeasible. Therefore, this study adopted a strategy of selling the mined Bitcoins daily at their closing price, juxtaposing the revenue thus generated against that of a PV solar power plant selling electricity at state-mandated rates. The design process of the PV system commenced with a review of existing methodologies and software applications. The available types of solar power plants, either grid-connected or off-grid, were both deemed viable for this research. However, the choice between these types was ultimately guided by economic policy considerations and initial capital availability. The study proposed a model of energy exchange with the national grid during peak production hours (from sunrise to sunset) in return for grid electricity to power the mining operation during nocturnal hours; Due to the high cost of storing energy in batteries and their limited lifespan, which is often affected by frequent charging and discharging cycles, many systems consider energy exchange with the mains grid as a more viable option. In fact, this hybrid system is designed to prioritize exporting the majority of generated energy to the national grid during peak production hours, while importing an equivalent amount during periods of low production, such as during the night. This approach helps mitigate the expenses associated with battery storage and maintenance while ensuring a steady energy supply to meet demand fluctuations. The chosen simulation software for the PV system was PVsyst version 7.3, a highly respected tool developed by specialists in Geneva, Switzerland. This software is renowned for its ability to accurately measure energy output based on the PV system's geographic location, thereby aiding in the design process. Its comprehensive database, which includes geographic and meteorological information, various panel and equipment types, alongside capabilities for rapid and precise calculations and extensive reporting, constitute its primary advantages [71].

Table 2
Details of mining system.

Manufacturer/Model	Release Date	Hashrate (Th/s)	Power (W)	Price ($)	Weight (g)
Bitmain/Antminer S17 Pro 50	Apr-19	50	1975	1950	9500
Bitmain/Antminer S17 Pro 56	Jun-19	56	2212	1100	9500
Bitmain/Antminer S17 Pro 53	Apr-19	53	2094	1478	9500
Support And Installation					
520 $ for each miner					

The focus of this research was the United Arab Emirates, a leading producer of solar energy. This nation has established the world's largest PV and CSP plants (a 2 GW PV plant, projected to expand to 5 GW by 2030, and a 100 MW CSP plant [72]). The chosen site for this study was in proximity to Abu Dhabi, with meteorological data and irradiance levels obtained using METEONORM (see Fig. 1).

The design aimed for a high-durability, efficient power plant over the long term, thus opting for fixed panels to minimize mechanical issues. The panel's tilt angle was set at 24.6°, aligning with the efficiency peak and minimizing energy loss. To maximize solar energy capture in the northern hemisphere, the panels were oriented due south (azimuth angle of 0) (see Fig. 2).

The objective was to design a solar power plant capable of supporting a 9.3 MWp Bitcoin farm, requiring approximately 200 MWh of energy daily. The simulated solar power plant needed a minimum capacity of 50.91 MWp system power to adequately supply the Bitcoin farm's electricity demands. The nominal power of the PV system has been selected to ensure that the total electricity it generates over a year closely matches the annual electricity consumption of Bitcoin mining. Component selection was driven by the goal of achieving high energy efficiency over a defined area. Recent advancements in solar panel technology have led to system efficiencies exceeding 20 % [73]. The plant was segmented into four phases, each with a capacity of 12.5 MW, and diverse PV modules and converters were selected for each phase. Four types of panels, each with an efficiency exceeding 20 % and at a reasonable price point, were chosen. Converters were selected with the aim of minimizing energy loss. Given the plant's substantial capacity requirements, components from various manufacturers were utilized to simulate real-world procurement challenges.

Tables 3 and 4 present the specifics of the PV modules and converters for each phase, along with their respective online store prices, exclusive of shipping costs. It is important to note that real-world plant design necessitates the consideration of local suppliers for both design and component procurement.

In the realm of component selection, the incorporation of energy storage systems into the power plant was contemplated. Such a system would enable the plant to operate independently. However, the study's proposed solution involved energy swapping with the national grid, whereby the energy injected into the grid during solar periods would be equivalent to the energy drawn from the grid when solar production was not feasible. This strategy not only supports the national grid during peak consumption periods but also leverages surplus energy during times of low demand.

For heightened simulation accuracy, the quality of sunlight at the chosen location required precise measurement. Although manual measurement entails significant computational costs, specialized equipment can accurately assess the light quality at the specified location. This study employed www.suncalc.org to analyze shadow casting in the vicinity. Utilizing AI algorithms, this source measures the horizon line and assesses light quality at the designated location. Shadow analysis was conducted by inputting the geographical coordinates, and the simulation predicted light quality from 2001 to 2100. Selected solar azimuth and elevation values across this time range were inputted, yielding horizon line data which was subsequently illustrated in Fig. 3.

For an economic evaluation, initial component prices were gathered from online commercial platforms. Installation costs for the panels were approximated at $2.9 per panel. Comprehensive economic analysis also accounted for additional expenses such as cleaning, maintenance, insurance, support, warranties, rent, etc. According to Table 5, the annual operating costs for the power plant were estimated to be around $902,000.

The investment aspect of the study examined available information regarding investment companies in this sector, revealing that over 90 % of initial costs are typically covered through loans and similar financial instruments. The study hence considered personal capital and three types of loans. Table 6 outlines all available capital, encompassing loans with their respective interest rates, personal capital, etc. The power plant's inception was set in 2020, with an operational lifespan projected at 25 years [74]. The economic calculations also necessitated defining a component degradation rate as a percentage per year, which was set at −0.43 % [75]. Inflation was factored in at 2.4 % (dollar inflation), and the discount rate was established at 5 % [76,77]. For this research, electricity prices in the UAE were set at 9.4 cents during peak hours and 5.6 cents during off-peak periods [72,77].

An environmental assessment using PVsyst software was conducted, which included calculating the annual electricity generation compared to carbon emissions from fossil fuel use in the UAE's electricity grid. This calculation took into account the carbon produced by equipment (as included in the software's database) and the rate of degradation [75]. The carbon balance was determined using Eq. (3):

$$E_G \times PL \times LCE_G - LCE_S = CB \tag{3}$$

Fig. 1. Suggested location map for facilities and geographical characteristics data.

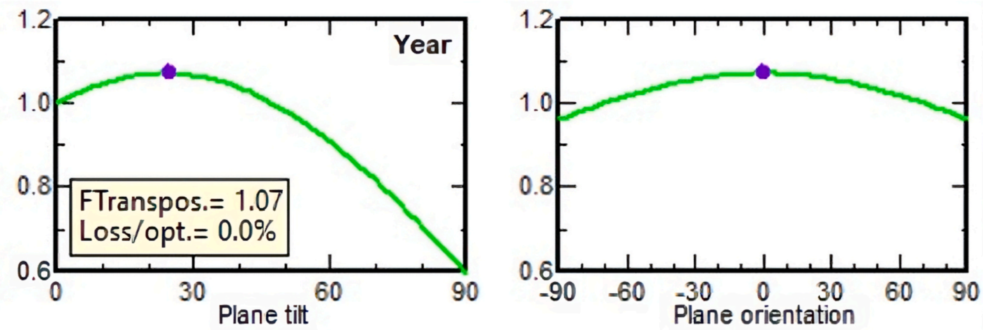

Fig. 2. Module orientation and tilt for minimal energy loss.

Table 3
Details of PV modules.

Phase	Manufacturer/Model	Type	Module power (Wp)	V_{oc} (V)	V_{mp} (V)	I_{sc} (A)	I_{mp} (A)	Tol (−/+%)	Eff (%)	Price ($)
1	Longi Solar/LR4-72 HPH 450 M G2	Si-mono	450	49.3	41.5	11.6	10.85	1.5	22.73	260
2	Risen Solar/RSM-156-6-430-M	Si-mono	430	52.4	43.6	10.47	9.87	3	22.67	218
3	SunPower/SPR-P3-415-COM-1500	Si-mono	415	54.1	45	9.9	9.22	3	22.17	291
4	Trina Solar/TSM-DE18M-(II)-480	Si-mono	480	50.8	42	11.99	11.42	3	21.76	346

Note: Standard Test Condition (STC); Irradiance: 1000 W/m2; Cell Temperature: 25 °C; Air Mass: 1.5; acc. to IEC 60904.

Table 4
Details of on-grid Inverters.

Phase	Manufacturer/Model	Max. DC input power (kW) Max. DC input voltage (V)	Grid Voltage (V)	Nominal AC Power (kVA)	Max. Efficiency (%)
1,3	SMA/Sunny Central 2500-EV	6250 1500	550	2500	98.56
2,4	SMA/Sunny Central 4000 UP	7000 1500	600	4000	98.79

E_G = Energy injected into the Grid [MWh]
PL = Project Lifetime [Year]
LCE_G = Life Cycle Emissions Grid [gCO_2/kWh]
LCE_S = Life Cycle Emissions System [tCO_2]
CB = Carbon Balance.

Relevant data such as LCE Grid and LCE System are accessible in the software's database [71].

Finally, the study's progress is succinctly summarized in the flowchart provided in Fig. 4, illustrating the key stages of the research methodology.

4. Results & discussion

4.1. PV system analysis

In this research, we designed a Bitcoin farm and a supporting photovoltaic (PV) power plant to investigate the environmental and economic efficacy of solar-powered Bitcoin mining. The power plant was conceptualized with a 50.91 MW nominal capacity, employing monocrystalline solar panels for their superior efficiency. Given the desert location of the plant and the potential risk to mechanical tracking systems, the use of solar panels with mechanical trackers was deemed impractical [78]. Based on the specifications provided by the software regarding space requirements, the panels were spaced 2.7 m apart to minimize shadow-induced losses, considering spatial limitations. Buildings for network control and other essential infrastructure were included to enhance the realism of the simulation. The system requires approximately 25.5 ha of space.

Table 7 details the GlobHor and DiffHor indices, representing horizontal solar irradiance and diffuse horizontal solar irradiance,

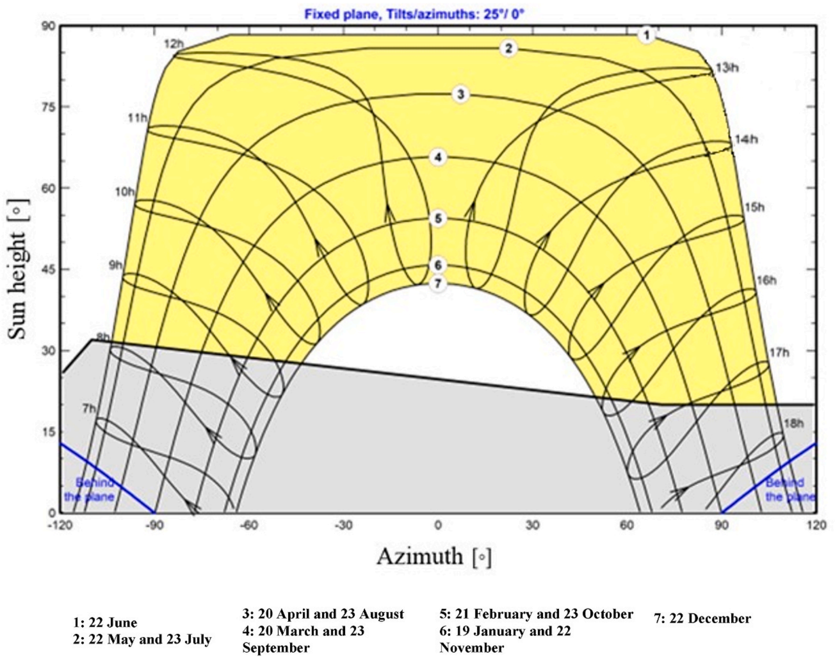

Fig. 3. Solar horizon and near shading.

Table 5
Economic evaluation for PV system.

Materials	Quantity	Total ($)
PV modules	115224	31,890,904
Inverter	14	175,896
Other components	–	159,081
Studies and analysis	–	36,711
Installation	–	401,659
Insurance	–	34,875
Total installation costs	–	33,034,706
Operating costs (OPEX) per year	–	902,263

Table 6
Details of Financing.

Type of Capital/Loan	Amount ($)	Interest Rate	Repayment Period (years)
Redeemable with fixed annuity	11,013,300	1.50 %	20
Redeemable with fixed amortization	12,237,000	1.50 %	25
Interest-only bullet loan	7,342,200	2 %	15
Own funds	2,437,627	–	–
Total	33,030,127		

respectively. The system receives 2032.2 kWh/m^2 from direct solar radiation and 929.3 kWh/m^2 from indirect or reflected light, peaking in May, June, and July. The column T_Amb indicates the ambient temperature surrounding the PV system, with a maximum of 36.7 °C in July and a minimum of 18.62 °C in January, averaging 28.52 °C annually. GlobInc and GlobEff columns show the solar irradiance on inclined surfaces and effective solar irradiance. The annual energy received on the inclined surface is 2175.1 kWh/m^2, deemed satisfactory given the location and optimal angle of the panels. After accounting for losses due to dust and shadows, the effective irradiance for the year is 1904.6 kWh/m^2. EArray denotes the electrical energy generated by the arrays before the inverter, and E_Grid shows the electricity injected into the grid. The system produces approximately 80.890 GWh annually. The performance ratio, listed last, averages 0.73 annually, considered acceptable given the specific conditions of the proposed PV system.

Fig. 5 presents a Sankey diagram illustrating the solar energy input and output, accounting for all energy losses from array configuration, converters, etc. The diagram shows that shadowing causes the most significant energy loss (11.7 %), impacting the system's performance ratio. In the array section, the primary energy loss is due to high temperatures reducing panel efficiency. The diagram further indicates losses from PV module mismatch (2.1 %), inverter operation (1.6 %), and cabling (1.1 %). Despite high direct

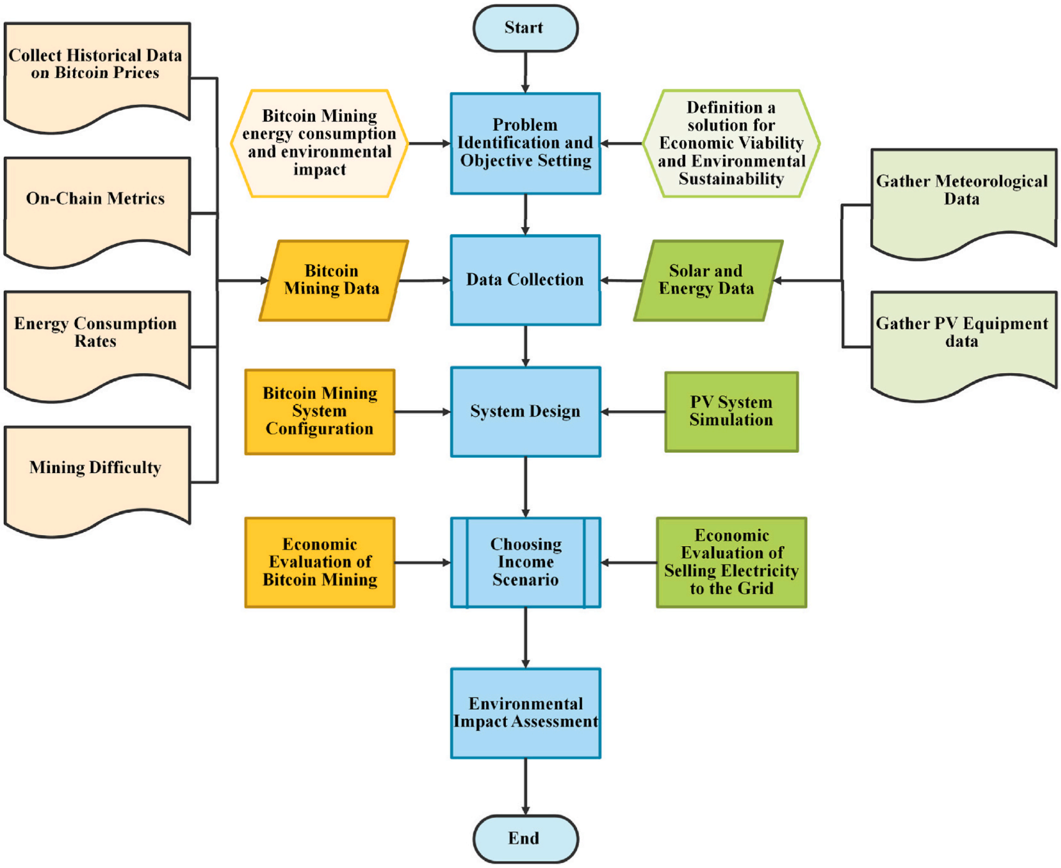

Fig. 4. Flowchart of the study's methodology and key stages.

Table 7
Balances and main results.

	GlobHor	DiffHor	T_Amb	GlobInc	GlobEff	EArray	E_Grid	PR
	kWh/m^2	kWh/m^2	°C	kWh/m^2	kWh/m^2	MWh	MWh	ratio
January	120.5	49.6	18.62	156.5	129	5875	5774	0.724
February	131.5	60.6	20.06	158.1	136.7	6192	6088	0.756
March	166.4	82	23.96	181.9	159.7	7111	6993	0.755
April	189.8	88.5	28.51	191.6	172.1	7452	7328	0.751
May	223.3	92.1	33.25	209.2	189.7	7953	7824	0.735
June	218.5	103.4	34.31	198.6	179.3	7534	7413	0.733
July	204	107.1	36.7	189.1	170.3	7147	7034	0.731
August	192.3	105	36.57	188.5	169.1	7021	6908	0.72
September	181	77.6	33.46	192.9	173	7262	7144	0.727
October	162	64.4	30.39	190.2	164.6	7009	6892	0.712
November	130.2	49.9	25.12	168.5	140.1	6195	6091	0.71
December	113	49.1	20.75	150.1	121	5495	5402	0.707
Year	2032.3	929.3	28.52	2175.1	1904.6	82246	80890	0.73

solar radiation at the site, excessive temperatures reduce PV array outputs (12 %).

One of PVsyst software's outputs is the normalized power output chart based on IEC-61424 standards [71]. This chart facilitates comparison of outputs, losses, and efficiency across different power plants. The chart uses purple to represent energy loss in the solar array and green for system energy loss. Net energy production is also indicated. Notably, energy output decreases in July and August due to excessive temperatures (see Fig. 6).

For economic efficiency comparison, the power plant was assessed for electricity sales at government rates:

Fig. 7 displays a cumulative profit chart over the power plant's lifespan. The capital payback period is approximately 8 years, factoring in inflation, discount rate, and aging rate; This assessment pertains to the scenario where the power plant's sole revenue source is the sale of electricity to the grid. The repayment of a 6-million-dollar interest-only bullet loan occurs in 2038, resulting in

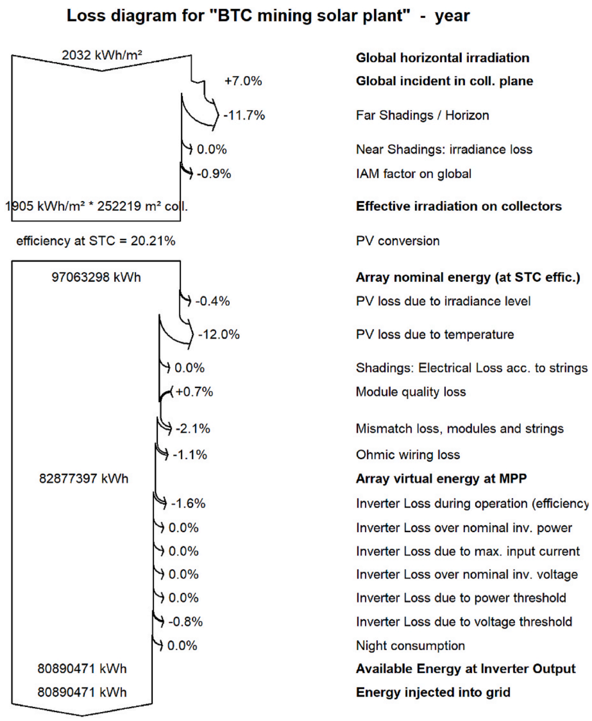

Fig. 5. Loss diagram of the 50 50.91 MWp PV system calculated by PVsyst software.

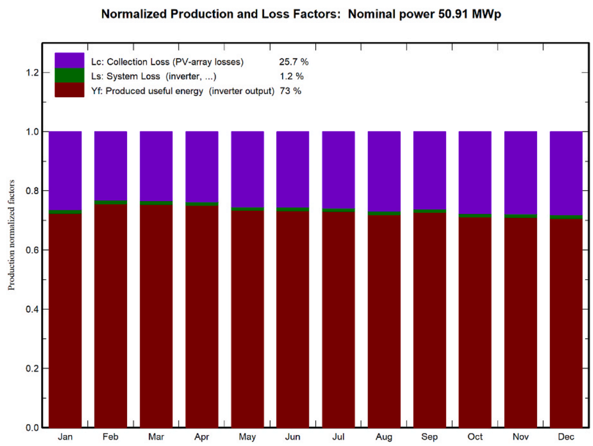

Fig. 6. Monthly Normalized productions with losses.

negative revenue that year. PVsyst's economic indicators include a Net Present Value (NPV) of approximately 48 million dollars, a Return on Investment (ROI) of 146 %, and an Internal Rate of Return (IRR) of 160 %. The Levelized Cost of Energy (LCOE) for the proposed PV system is 0.0335 USD/kWh.

4.2. Bitcoin mining system analysis

Evaluating a PV system for powering a Bitcoin mining farm underscores the viability of this approach. As shown in Table 7, the PV system's output varies monthly, while the mining farm's electricity consumption remains relatively constant, differing only due to the number of days in each month. The miner selection ensures the annual power production of the PV system, with a Power Usage Effectiveness (PUE) rate of 1.1, matches the consumption. The average monthly consumption for the mining system is about 6745 MWh. Table 8 highlights the energy consumption of the PV and Bitcoin mining systems, showing the differences across months. Energy consumption is averaged over a 365.25-day year; the mining system's annual energy use nearly matches the PV system's production, with a negligible surplus. Due to the PV system's varying power injection throughout the year, an energy swap scenario with the

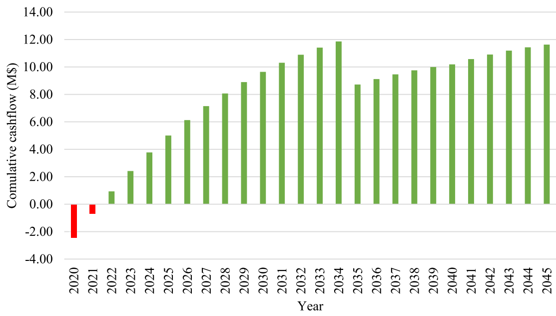

Fig. 7. Cumulative cash flow chart of PV system revenue from the sale of electricity to the grid.

Table 8
differences between the production of 50.91 MWp PV system and consumption of Bitcoin farm across months.

Months	E_Grid (MWh)	BTC Mining consumption (MWh)	Difference (MWh)
January	5774	6731	−957
February	6088	6731	−643
March	6993	6731	262
April	7328	6731	598
May	7824	6731	1094
June	7413	6731	682
July	7034	6731	304
August	6908	6731	177
September	7144	6731	414
October	6892	6731	161
November	6091	6731	−640
December	5402	6731	−1328
Total	80890	80766	124

national grid was considered to offset shortages and redistribute surplus energy. However, due to the year-long balance of consumption and production, the calculations for electricity trade with the national grid, and assessments of revenue or cost from electricity exchange, were excluded.

The capital required for this system is approximately 33 million dollars for the PV segment and 9 million dollars for the Bitcoin mining system. The miners were selected for their efficiency and optimized electricity usage. Due to the difficulty in long-term Bitcoin price prediction, the study initially sought to use available information for profitability and economic evaluation; thus, a comprehensive evaluation was conducted until November 2023. The data's credibility is bolstered by its sourcing from financial archives and On_chain indices from data collection websites [70].

In the simulation, the Bitcoin mining budget was fully considered as personal capital, but the economic evaluation for funding the PV system included both loan and non-loan scenarios. For the loan scenario, the repayment period started in 2020. Fig. 8 shows the cumulative cash flow chart for both scenarios. In the loan scenario, cash flow turns positive after about 15 months, but in the non-loan scenario, it takes approximately 3.5 years, including all annual power plant expenses. Considering that the PV system's payback period, relying solely on revenue from the conventional sale of electricity to the grid, spans approximately 8.1 years, the significantly reduced payback period of 3.5 years in the Bitcoin mining scenario represents a markedly advantageous financial proposition. Based on data available until November 2023, the cash flow considering the loan is approximately 27 million dollars. From the fourth year onwards, the energy production cost for Bitcoin mining will be nearly equal to the plant's annual operating costs (about 0.9 million dollars per year), resulting in an energy production cost of approximately 0.011 USD/kWh.

As the network difficulty of Bitcoin mining increases over time, the efficiency of mining devices decreases. According to the Cambridge Bitcoin Electricity Consumption Index (CBECI) [79], the efficiency coefficient of miners will decline to zero over five years, reducing annually by 0.2. Two scenarios for enhanced profitability can be considered: 1) Evaluating the profitability of new mining devices against the profitability threshold of the currently used miners and making decisions about updates based on their cost; 2) Selling electricity to the grid at regulated rates. Owing to the system's flexibility, the selection of either scenario can be readily executed, necessitating merely an economic assessment relevant to the period in question.

Given the findings, the proposed system demonstrates suitable profitability. Considering the cryptocurrency market's volatility, long-term price prediction for economic evaluation is nearly impossible. However, the calculations show that Bitcoin mining profitability with a PV system for energy supply, and plant funding under the described loan conditions, can generate about 27 million dollars in positive cash flow by the end of 2023; this occurs with fixed-rate sales in ten years, and the rate of investment return with the Bitcoin mining PV system is significantly faster. Comparing the economic scenarios of Bitcoin mining income with power plant electricity sales, the use of the system with the described methods shows that investment is economically optimal.

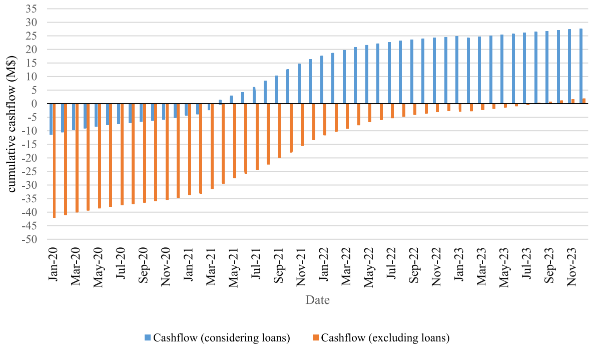

Fig. 8. Cumulative cashflow from Bitcoin mining utilizing the PV system.

4.3. *Environmental analysis of the PV system*

The annual output of the power plant was calculated based on the carbon production rate per kilowatt-hour for the UAE. Moreover, an in-depth examination of the Life Cycle Emissions (LCE) — the carbon emissions resulting from the manufacturing of power plant components — revealed that the production process generates approximately 22,000 tons of emissions, encompassing modules, inverters, and support structures. According to Fig. 9, the carbon emission prevention in this power plant over 25 years is around 1.237 million tons. On average, this prevents the annual emission of approximately 50,000 tons of carbon, equivalent to removing about 10,700 regular cars from the roads [80]. The primary energy consumption for global Bitcoin mining is fossil fuels, highlighting the potential carbon emission reduction by implementing such systems. However, the environmental impacts of Bitcoin mining are not limited to carbon emissions; a notable concern regarding Bitcoin's sustainability is the generation of electronic waste. This waste stems from the frequent upgrading and subsequent discarding of Bitcoin mining equipment. Alex de Vries in a previous research reported that each Bitcoin transaction generates approximately 134 g of electronic waste [30]. In a more recent study by the same author, it is reported that the annual production of Bitcoin e-waste up until May 2021 amounted to 30.7 metric kilotons. The study further suggests that at peak Bitcoin price levels observed in early 2021, Bitcoin could generate up to 64.4 metric kilotons of e-waste. Additionally, it is indicated that an average of 272 g of e-waste is produced per transaction processed on the Bitcoin blockchain [81]. In contrast, a conventional centralized financial transaction system, such as Visa, produces only 0.0045 g of electronic waste per transaction [30]. Given the data and scenarios discussed, it is important to recognize that the decision to upgrade Bitcoin miners in this study should be contingent on the prevailing Bitcoin price levels and the cost of electricity within the network. While determining the optimal timing and economic conditions for such upgrades falls outside the scope of this study, an estimation of the electronic waste that would result from such a decision can still be made. Specifically, replacing 4000 Bitcoin miners, as detailed in Table 2, each weighing approximately 9500 g, would generate roughly 38 metric kilotons of electronic waste. This estimation underscores the significant environmental impact associated with hardware upgrades in Bitcoin mining systems. The environmental consequences of this electronic waste are profound, as it contains hazardous materials that can leach into the soil and water, leading to significant environmental and health risks [82,83]. Nevertheless, programs can be implemented to mitigate environmental impacts. In 2019, global waste recycling rates were reported at approximately 17.4 % [84], highlighting a significant shortfall in electronic recycling programs that comply with environmental regulations. Community-based recycling initiatives, therefore, have the potential to reduce the adverse effects associated with improper e-waste disposal [85]. Additionally, enhancing the design of mining equipment by utilizing more durable materials can extend the lifespan of the hardware, thereby reducing e-waste generation. Promoting a circular economy—through recycling or repurposing rather than discarding—can also play a crucial role in effective e-waste management [86].

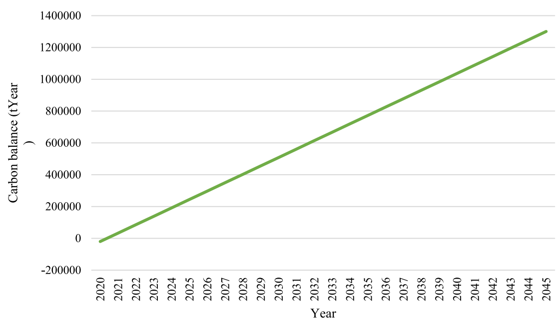

Fig. 9. Yearly carbon emission balance.

5. Conclusion

This study assessed the environmental and economic benefits of using renewable energy from a PV system for Bitcoin mining in the UAE. The study's innovation lies in its accurate economic evaluation based on documented historical information and comprehensive simulations, minimizing simplifying assumptions to ensure results closely reflect real-world conditions. A 50.91 MWp PV system was designed to power a 9.3 MWp Bitcoin mining farm, ensuring continuous electricity supply. Instead of a separate storage system, energy swapping with the national grid was utilized. The design results show that with tariffs of 0.056 dollars for off-peak consumption hours and 0.094 dollars for peak hours per kilowatt, the power plant's initial and ongoing costs have an 8.1-year payback period. However, the income from the Bitcoin mining system will generate positive cash flow and repay all initial and ongoing costs in approximately 3.5 years (considering all costs from the start of 2020 to the end of 2023). If a loan is considered for the power plant in this system, the cash flow at the end of the period (end of 2023) will be around 27 million dollars. All these calculations were performed under the assumption that all mined Bitcoins are sold daily. Furthermore, from an environmental perspective, the system prevents the emission of approximately 1.237 million tons of carbon over 25 years. These results demonstrate that using renewable energy for Bitcoin mining is both economically and environmentally viable, potentially addressing environmental concerns about such systems while offering significant economic benefits. In the present study, we have emphasized the use of documented information from reliable sources to minimize assumptions in our analyses. However, due to the unavailability of daily energy price data, we employed fixed rates for peak and off-peak periods. This approach facilitated a more accurate analysis within the available timeframe, although higher precision could be achieved with more detailed pricing data. Additionally, in the absence of a comprehensive equipment price archive specific to the proposed project location, pricing information for the components required to establish the power plant and Bitcoin mining farm was sourced from online platforms. While this may introduce slight variations in the financial analysis of initial capital, it does not significantly impact the overall findings of the study.

The income analysis and economic evaluation were conducted using information limited to the period from 2020 to 2023, with a daily income scenario from mining and selling Bitcoin. This approach may yield different results compared to other sales scenarios across different time periods.

Our research focuses on solar energy in the Middle East due to the region's advantageous geographic conditions. The UAE was selected as the case study for simulation and analysis, grounding the primary information and statistics in the specific geographical and economic conditions of this country. Consequently, the results may not be universally applicable to other settings.

Future research should expand to a more comprehensive review of renewable energy systems for Bitcoin and other cryptocurrency mining. This should include an exploration of various energy sources such as wind, geothermal, and nuclear power, with efficiency assessments tailored to specific geographic contexts. Additionally, leveraging historical data for extended time periods could provide deeper insights into the economic and environmental impacts of these energy systems. Implementing machine learning techniques to optimize income scenarios—such as determining the optimal times to mine and sell Bitcoin versus selling electricity back to the grid—could also offer valuable insights into profitability under varying conditions and timeframes. These future directions present opportunities to further enhance the sustainability and economic viability of cryptocurrency mining.

Investors aiming to generate income from digital currency mining are advised to consider implementing such a system, particularly if local policymakers are supportive. Collaborating with local authorities can facilitate the integration of energy systems that support local networks during peak consumption periods, while also ensuring minimal environmental impact. Additionally, the findings suggest that energy sector officials could develop more attractive proposals to entice investors, thereby fostering greater investment in the energy sector and enhancing the overall economic viability of renewable energy projects.

CRediT authorship contribution statement

Ali Hakimi: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Mohammad-Mahdi Pazuki:** Writing – review & editing, Methodology, Investigation, Formal analysis, Conceptualization. **Mohsen Salimi:** Writing – review & editing, Methodology, Investigation, Formal analysis, Conceptualization. **Majid Amidpour:** Writing – review & editing, Supervision, Project administration, Investigation, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.heliyon.2024.e39765.

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