



An integrated landfill gas-to-energy and Bitcoin mining framework

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1. Introduction

Growing methane emissions pose a significant challenge for climate change mitigation. Methane emissions, which have persistently risen since the early-2000s, are projected to continue their upward trajectory until 2050 unless substantial international mitigation efforts are enacted (EPA, 2020; IEA, 2023b; Saunio et al., 2020; UNEPCCAC, 2022). Methane, with a 100-year Global Warming Potential (GWP100) of 27–30 times that of CO₂ presents a significant and long-lasting challenge to climate mitigation efforts (Cicerone and Oremland, 1988; IPCC et al., 2022; Wuebbles and Hayhoe, 2002). Emission sources are multifaceted, encompassing both natural phenomena and anthropogenic activities across sectors like agriculture, waste management, and energy (Bousquet et al., 2006; EPA, 2020; IEA, 2023a; IGSD, 2023; UNEP, 2020).

The immediate need for methane mitigation becomes more critical as delays escalate future mitigation complexity and costs, which are already projected to be two to four times higher than if addressed in the 2010s (UNEP, 2020). Focused mitigation initiatives up to 2030 could yield a reduction in warming rates by more than 25%; conversely, postponement could limit the impact to a mere 5% reduction (Ocko et al., 2021). Recognizing the importance of methane mitigation, over 150 countries have endorsed the Global Methane Pledge (GMP) (www.globalmethanepledge.org).

While a wide range of proposed methane mitigation strategies exist (IGSD, 2023; Li et al., 2015; Nisbet et al., 2020; Ocko et al., 2021), no single approach can fully address anthropogenic emissions, necessitating diverse interventions across agriculture, waste management, and energy sectors (Ayandele et al., 2022; IEA, 2022, 2023b; Malley et al., 2023; Nisbet et al., 2020; Ocko et al., 2021; Rutherford et al., 2021; Zaks

et al., 2011), as well as behavioral change (Hoy et al., 2023). However, concerns remain about the slow pace of mitigation implementation relative to global needs (Olczak et al., 2023; UNEP, 2020), with factors such as capital-intensive infrastructure, uncertain revenue streams, and regulatory environments impacting progress (Li et al., 2015; Murray et al., 2017; Peng et al., 2023).

Economic factors critically influence the pace of methane mitigation deployment. Financial levers, such as tax credits for methane-derived biofuels, have shown efficacy in various regions (Erickson et al., 2023; Li et al., 2015; Murray et al., 2017) and carbon credit programs are widely used (EC, 2020; Lorenzato et al., 2022). Yet, macroeconomic pressures like economic downturns and high interest rates present barriers to funding capital-intensive projects that only accrue benefits over the long-term, into the distant future (Polasky and Dampha, 2021). This raises the question of whether there are alternative, rapidly-scalable, and financially sustainable ways to incentivize methane mitigation (Agerton et al., 2023).

Hoy et al. (2023) emphasized the need for government subsidies for methane mitigation. The private sector often responds more swiftly to price incentives for climate mitigation efforts than public utilities (Agerton et al., 2023). However, the success of government subsidization depends on policy implementation in diverse jurisdictions that vary in socioeconomic context and governance capacity. Bitcoin's economic incentives, available globally for miners in any location, may offer an innovative solution for encouraging methane mitigation without the need for government incentives, presenting a scalable and novel solution for rapid deployment.

The Bitcoin mining approach has potential for revenue generation and cost recovery, accelerating landfill gas (LFG) mitigation efforts by making them more profitable compared to other available revenue

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streams (Rudd et al., 2023). The U.S. government has, in fact, acknowledged the prospects of utilizing stranded methane “produced during natural gas drilling and transmission, and by oil wells, landfills, sewage treatment, and agricultural processes” (OSTP, 2022: 23) for Bitcoin mining.

The integration of renewable and waste energy sources with Bitcoin mining is a growing field, aiming to address the high energy consumption associated with Bitcoin operations. Bitcoin miners, sensitive to electricity costs, often co-locate with renewable energy projects (Ibañez and Freier, 2023; Lal et al., 2024; Niaz et al., 2022). Several studies have explored this synergy, highlighting the potential for Bitcoin mining to act as a flexible load that can balance intermittent renewable energy supply. For example, Lal et al. (2023) examined the potential for Bitcoin mining to integrate with solar and wind energy, concluding that such integration could enhance grid stability and provide a financial return on investment for renewable projects. Niaz et al. (2022) conducted a case study in Texas, where Bitcoin mining operations were co-located with wind and solar farms to mitigate curtailment issues, allowing for more efficient use of generated energy, reducing waste and improving overall economic feasibility. Research by Vazquez and Crumbley (2022) explored the application of flared gas from oil and gas operations in Bitcoin mining, illustrating another successful example of integrating stranded energy resources. These studies demonstrated that Bitcoin mining could act as a viable solution for utilizing energy that would otherwise be wasted, providing economic incentives for operators while contributing to emission reduction efforts.

The results from wind and solar integration studies suggest that potential also exists to co-locate private Bitcoin mining operations with industrial sources of methane emissions (Rudd et al., 2023; Vazquez and Crumbley, 2022). The novelty of our paper lies in its emphasis on landfill gas-to-energy (LFGTE) systems, a less-explored avenue. An LFGTE approach provides a unique opportunity to destroy methane emissions from landfills, transforming a potent greenhouse gas into a valuable energy source that can be instantly monetized, using Bitcoin mining, in a global market.

By examining the scalability and economic viability of bitcoin mining as a market-driven mitigation strategy, our aim in this paper is to contribute to the global endeavor to curtail methane emissions, offering a novel perspective on combining a disruptive new financial technology with renewable energy projects for environmental sustainability. Our investigation focuses on the economic and environmental viability of leveraging bitcoin mining to support and enhance methane mitigation efforts at landfill sites. Our model, employing a Monte Carlo simulation, establishes a flexible framework for evaluating integrated Bitcoin mining and LFGTE projects across a variety of scenarios. While this paper primarily focuses on a landfill example, the underlying principles and findings have implications for wider applications, including orphaned oil and gas wells (Lorenzato et al., 2022), wastewater treatment plants, farms, and agricultural processing operations. The versatility of the approach suggests potential for adaptation and scalability, offering insights into the broader utility of bitcoin mining in addressing the global challenge of methane emissions.

2. Background

2.1. Landfill gas to energy

LFGTE projects play an important role in environmental stewardship by capturing methane and converting it into a renewable energy source. These projects not only mitigate the release of methane into the atmosphere, thereby significantly reducing greenhouse gas emissions and providing social benefits (Jaramillo and Matthews, 2005), but also contribute to the diversification of energy sources and reduction of harmful leachates and other harmful emissions of gases (Ghosh et al., 2023). The lifecycle of converting landfill methane into energy encompasses several stages (Alexander et al., 2005; EPA, 2012, 2021, 2023b),

beginning with the collection of LFG. A proportion of that mixture, depending on landfill age and other variables (Alexander et al., 2005), is methane that would rapidly exacerbate global warming if not destroyed.

Advanced processing transforms LFG into fuel suitable for generating electricity or thermal energy, or for further cleaning and processing into automobile fuels or natural gas (EPA, 2023b; Kabeyi and Olanrewaju, 2022). In addition to direct electricity production, LFGTE projects offer the potential for harnessing low-grade waste heat for applications such as district heating (Werner, 2017), further enhancing the energy utility of the process (EPA, 2012).

The economic landscape of these projects is influenced by local and regulatory contexts, which can enable access to various financial incentives like carbon credits (Li et al., 2015). These incentives, alongside the revenue generated from the sale of biofuels and electricity, underscore the multifaceted benefits of LFGTE projects. Through these mechanisms, LFGTE projects embody a practical application of circular economy principles, transforming waste into diverse revenue streams (Fig. 1) while bolstering environmental and public health.

2.2. Bitcoin mining

Bitcoin operates on a Proof-of-Work (PoW) mechanism, requiring approximately 0.63 zetahash per second (6.3×10^{21} hash/s) as of August 2024 (<https://data.hashrateindex.com/network-data/btc>). As of August 2024, Bitcoin, the largest computer network in the world, consumes electricity at an annualized rate of about 151 TWh, accounting for 0.59% of global electricity consumption (<https://ccaf.io/cbnsi/cbeci/comparisons>). This substantial energy demand, while frequently criticized for environmental (de Vries et al., 2022; Xiao et al., 2023) and socio-economic (Howson and de Vries, 2022; Lally et al., 2022) reasons, underpins the Bitcoin network’s security, deterring fraudulent activity by making the financial and physical (energy) costs of unauthorized alterations prohibitive. Bitcoin’s PoW validation thus has the financial power to strongly disincentivize fraudulent behavior and, instead, increase levels of trust needed for pseudonymous financial transactions (Berg et al., 2020).

Miners generate blocks of financial transactions that constitute the backbone of Bitcoin’s global ledger. Bitcoin mining utilizes Application-Specific Integrated Circuit (ASIC) chips, specifically designed to deliver the intensive computational power required to compete for and solve SHA-256 cryptographic algorithms. Successfully solving these puzzles rewards miners with the right to create a new block and bestows both a block reward and all block transaction fees to the successful miner. Those earnings, paid in bitcoin, can either be held speculatively or swapped to local currencies to cover operational costs. All of Bitcoin’s 21-million token supply come into existence via mining: 19.8-million have been mined so far; and the remaining 1.2-million will be awarded in a logarithmically declining emission schedule until about 2140.

Bitcoin mining offers several unique advantages for LFGTE producers compared to traditional biofuel and electricity sales models, potentially making it a novel and compelling option for LFG utilization. These could be especially important in remote areas or in jurisdictions with limited capacity to finance long-term mitigation investments due to prohibitive upfront costs or high discount rates.

1. Global Market Access: Enables miners and landfill operators to tap into a worldwide customer base, overcoming regional limitations on energy or biofuel sales.
2. Dynamic Scalability: Facilitates the flexible utilization of LFGTE-generated electricity, optimizing the use of intermittent energy production or market demand.
3. Cost Savings: Can reduce or eliminate costs associated with grid connection and transmission losses for newly electrified renewable energy generating sites.

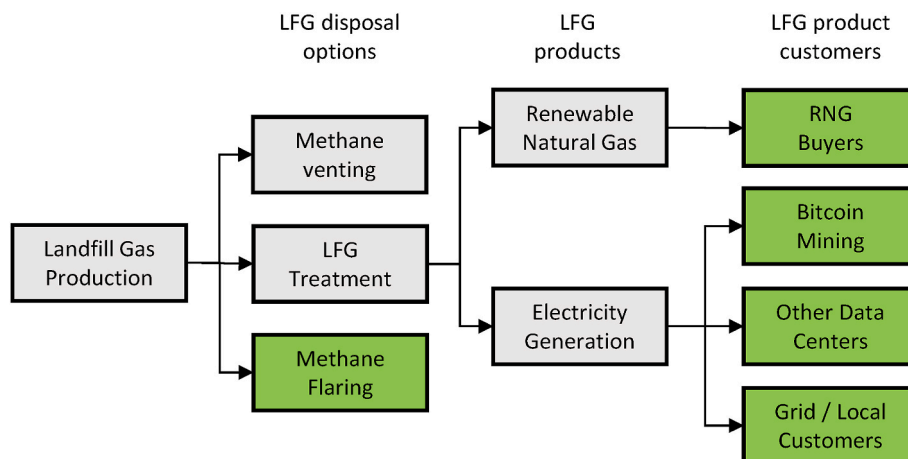


Fig. 1. Possible revenue generation sources (green fill) for solid waste disposal sites. Methane flaring is included as there are, depending on jurisdiction, possibilities to collect carbon credits. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

4. Infrastructure Independence: Bitcoin mining facilities can be set up at any site irrespective of electricity grid connections or communications infrastructure.

Venturing into Bitcoin mining introduces risks such as Bitcoin's price volatility and regulatory uncertainties. To mitigate these challenges, landfill operators might forge partnerships with seasoned miners, utilize financial instruments for hedging price risks, or adopt diverse business models from revenue sharing to Power Purchase Agreements (PPAs). Such strategic considerations are crucial as shifts in regulation and public perception can impact the viability and perception of Bitcoin mining endeavors.

The Nodal Power operation in Utah exemplifies the innovative integration of LFGTE projects with Bitcoin mining. Their 1.6-MW project transformed a site that actively flared landfill gas into one that utilizes methane to generate electricity for Bitcoin mining, showcasing a novel approach to resource utilization (see <https://youtu.be/XXJBUuijUV0?si=MI-7XqnCwVQhH19A>). Similarly, in New Mexico, Nodal acquired an operational, grid-tied LFGTE facility and integrated a behind-the-meter datacenter. This operation allows for the strategic dispatch of electricity between the grid and the datacenter, optimizing the use of landfill gas. Such dual-purpose applications not only introduce new revenue streams but may also enhance the electrical grid's resilience through miners' ability to rapidly adjust to grid demand fluctuations (Carter et al., 2023; Menati et al., 2023).

The infrastructure investment for converting a landfill site already harvesting gas into a Bitcoin mining power generation site is approximately \$2.5 million per MW, predominantly for the generator and ASICs. LFGTE companies often prefer compensating landfill owners with royalties on gross revenue, encouraging optimal LFG flow management while adhering to legal regulations, thus maximizing electricity production.

Given the Bitcoin network's fluctuating hashrate and price, the proportion of gross revenues can vary, making a royalty-based revenue sharing model beneficial for developers as a downside protection mechanism, while also offering landfill owners the potential for significant upside benefits.

3. Model development

Our study employs a Monte Carlo simulation model, developed with Lumina System's Analytica platform, to offer insights into the integration of LFGTE projects and Bitcoin mining operations. Monte Carlo simulation is particularly well-suited for this study due to the high level of uncertainty inherent in Bitcoin-LFGTE modeling, especially when

considering volatile Bitcoin market dynamics and variable electricity production costs. The Analytica platform is known for its strength in policy modeling, allowing construction of complex models that reflect real-world uncertainties and interdependencies in economic scenarios (Morgan and Henrion, 1990). Recently, it has been used to incorporate complex, uncertain parameters influencing financial viability in energy sector models (Milford et al., 2022). By using this Monte Carlo approach, it is possible to incorporate a wide range of uncertain parameters, such as the financial viability influenced by mining rig choice and electricity generation costs.

We employed a sample size of $n = 10,000$, utilizing median Latin hypercube sampling for robust scenario analysis, ensuring a comprehensive exploration of potential outcomes. Our approach captures a broad spectrum of high-level scenarios, focusing on the economic impacts and strategic opportunities presented by the integration of Bitcoin mining with LFGTE projects. Instead of using detailed landfill methane production modeling (i.e., following EPA, 2021), we drew electricity generation cost samples from a range of feasible options, enabling us to explore various strategic configurations and their implications for policy and investment decisions.

3.1. Landfill assumptions

We constructed the model based on the assumption that 10-m kWh of electricity (1.14 MW) would be available for bitcoin mining. This could be supplied by many low-flow facilities in the USA or by landfills with higher flow but which had other commitments for a portion of their electricity generation capacity. Working backwards, using EPA Landfill Methane Outreach Program (LMOP) guidance regarding the determinants of emissions (EPA, 2023b), this would imply a landfill producing roughly 7.8 million m^3/year LFG (527 SCFM) from a population base of around 65,000 people (assuming: 2.2 kg/person/year waste; 150 kg/m^3 waste to LFG production; 85% collection efficiency; 50% methane content; energy content of 10 kWh/m^3 LFG; 30% conversion electricity generation efficiency; and 0% electricity retained for landfill use). We recognize that our landfill assumptions are simple; however, if needed, the landfill side of the model could be fully expanded using established modeling tools that account for context-dependent factors such as organic content of the solid waste, age of the landfill, and climate (EPA, 2023b).

3.2. Landfill breakeven electricity production costs

Acknowledging the sensitivity of bitcoin mining's financial outcomes to electricity pricing, our analysis spans a range of feasible break-even

electricity production costs (c_{be}) for LFGTE projects. Tadesse and Lee (2024) recently estimated the cost of electricity production from landfills to range from USD \$0.03 to \$0.10/kWh. A synthesis of 2018 USA data found a levelized cost range of \$0.05 to \$0.068 per kWh for fully capitalized LFG electricity production (DOE, 2019). The LMOP manual (EPA, 2023b) suggested that LFG electricity costs ranged from \$0.025 to \$0.11/kWh and recommends a default assumption of \$0.065/kWh. Internationally, a variety of LFGTE electricity production costs have been reported: \$0.08/kWh at the Bantargebang landfill in Jakarta (Kurniawan et al., 2022); \$0.04/kWh in Delhi (Peng et al., 2023); and a levelized cost of \$0.1402 to \$0.2260/kWh in Beijing (Cudjoe et al., 2021). Based on the experience of our industry co-authors, we anticipate average cost-of-production for a low-flow landfill in the USA would be in the \$0.055/kWh range. This information suggests that our choice of drawing samples from within the \$0.01 to \$0.10/kWh range is a credible for our model, capturing production cost possibilities even in the tails of the cost distribution.

At the low-cost end of the spectrum, the model was fixed at a minimum cost of \$0.01/kWh; at the high-cost end, the production cost options ranged from \$0.07 to \$0.10/kWh in \$0.01 increments. For the base case outlined below, we used low and high prices of \$0.01 and \$0.10, respectively, and created a normal distribution of breakeven prices to sample from with the mean ($\mu = \$0.055$), truncated at the low and high breakeven prices (Fig. 2). The standard deviation (σ) was set as the low plus high feasible breakeven costs divided by five ($\sigma = \$0.020/\text{kWh}$). The range of plausible electricity production costs, in line with our own experience and available estimates in the literature, frame the economic landscape for LFGTE-derived electricity and aid in exploring the financial dynamics underpinning partnerships between landfill operators and bitcoin miners.

An important challenge for modeling integrated bitcoin mining at landfills is that business structure has an important impact on revenue sharing and financial performance for both the miner and landfill operator. These have important implications for the likelihood of speed and scaling of development.

The gross revenue share for landfill operators is typically within the 5% (SL_{min}) to 30% (SL_{max}) range for North American low-flow landfills. The landfill operators at these facilities would not typically produce any electricity, and the bitcoin miners would supply all capital and variable costs for generating electricity. For this model, we assume that landfills with higher potential for generating low-cost electricity would tend to be more highly compensated via increased levels of revenue sharing. For each sample (i) we drew randomly from across a uniform distribution range ($U_i = \text{uniform}[0,1]$) to calculate (Equation (1)) the revenue share

for landfill operators (S_L) as:

$$SL_i = SL_{min} + (U_i * [SL_{max} - SL_{min}]) \tag{1}$$

We calculated the miner revenue share accordingly ($SM_i = 1 - S_L$). Note that this revenue sharing arrangement could be easily structured to reflect more complicated situations such as, for instance, larger landfills that already have internal capacity to generate and sell surplus electricity to local electricity grids or industrial customers.

3.3. Bitcoin mining operations

Using the available electricity supply earmarked for bitcoin mining, we evaluated the number of high-performance ASIC mining rigs that would be needed to run the operation at full capacity. We considered three popular models: Bitmain’s Antminer S19j XP and both the air- and liquid-cooled versions of the Antminer S21. The selection reflects variations in hash rate, power consumption, and pricing, as detailed in Table 1.

An electricity supply of 10.0-m kWh/year allows for the deployment of 352 S19j XPs, 326 S21s, or 213 S21 hydro rigs. Commercially available 20-ft containers modified for bitcoin mining, and with 1440 kW/h power input capacity each, can handle up to 288 computers, allowing S21 hydro rigs to be deployed with minimal footprint and ancillary equipment requirements. The S19 XP and S21 air-cooled models would require a 40-ft container for full deployment. An analysis of older Bitmain S17 computers (McDonald et al., 2022) provides insights on container deployment costs and mining profitability on solar farms where the levelized cost of electricity was in the \$0.019 to \$0.051/kWh range for commercial container set-ups.

Table 1

Computer performance and pricing for three popular Bitcoin mining rigs.

Model ^a	Rig hashrate (TH/s)	Power consumption (w)	Cooling	Rig price (USD \$)
Antminer S19j XP	151	3247	Air	\$3473
Antminer S21	200	3500	Air	\$5000
Antminer S21 Hydro	335	5360	Liquid	\$6533

^a Information from <https://shop.bitmain.com/> (09 Feb 2024); note that mining rig prices can be volatile, depending on the price of bitcoin and other factors.

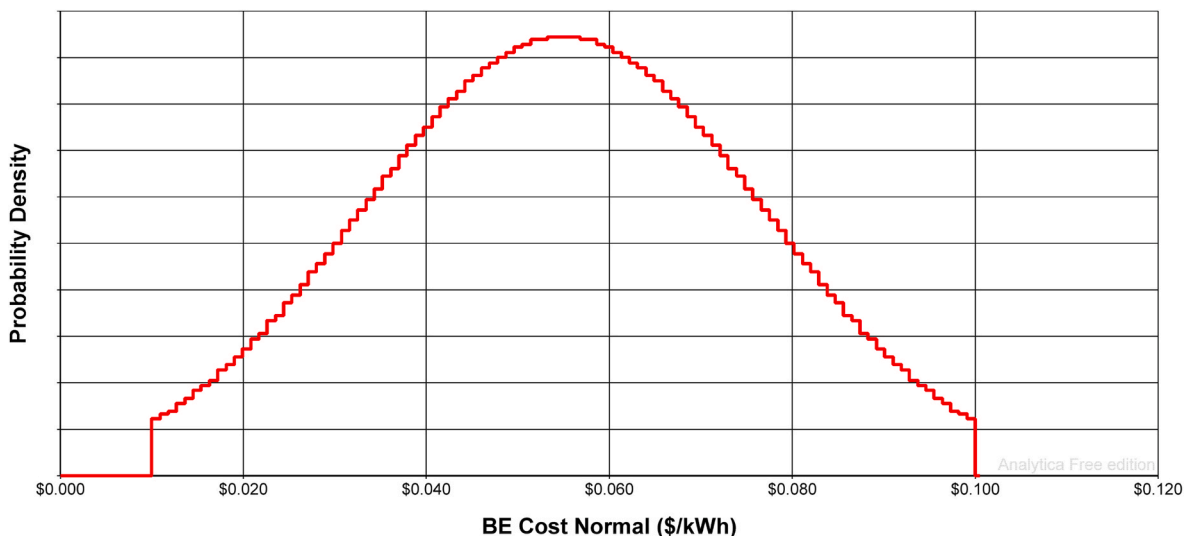


Fig. 2. Breakeven cost (p_{be}) needed to cover all expenses for LFG electricity production.

3.4. Mining financial assumptions

Pool fees were set at 2% and were deducted from the hash revenue split for each party. We assumed that miners paid for all additional capital and operating expenses. An influence diagram (Fig. 3) delineates the interconnected financial variables, including hashprice dynamics influenced by market conditions and operational decisions regarding electricity pricing and revenue sharing.

We assumed that non-electricity operating expenditures were 15% of electricity expenditures for all models of mining rig; often operating costs will fall below that level because variable costs associated with electricity generation can also cover mining facility operation costs. We focus on changes in revenue for both miners and landfill operators; given the rapidly changing pricing for rigs, advancing energy efficiency, and miners' propensity to switch rigs on and off as bitcoin price fluctuates, analyzing longer-term financial performance (e.g., IRR, NPV) would add more uncertainty into the model.

Hashprice (p_h , \$/TH/day) is a function of five factors (Equation (2)): the block reward (3.125 bitcoin/block from mid-April 2024 to approximately April 2028); average transaction fees per block; total network hashrate (TH); the difficulty adjustment, which is automatically modified every two weeks to maintain block creation time of about 10-min; and the USD \$ price of bitcoin (p_{BTC}). Excluding transaction fees, basic hashprice can be calculated as:

$$p_h = (p_{BTC})(3.125) \left(\frac{86,400}{\text{difficulty} \left[\frac{232}{\text{hashrate}} \right]} \right) \quad (2)$$

The model offers options of \$0.075 and \$0.150/TH/day for mean hashprice, p_h . We then applied a log-normal distribution transformation to mean p_h to approximate a price distribution with an extended upper tail. Bitcoin is a financial asset with a very strong positive skewness, making it very unlike most financial assets where price risk is more to the downside (Ang et al., 2022). For the baseline model, we used a mean hashprice of $p_h = \$0.075/\text{TH}/\text{day}$, which resulted in the hashprice distribution shown in Fig. 4.

Hashprice reached as high as \$0.40/TH/day during the 2020-21 bull run but the drastic expansion of the global computational power in preparation for the April 2024 halving kept hashprice subdued over 2023 and early-2024 (<https://data.hashrateindex.com/network-data/btc>). Counterbalancing the downward pressure of increased global Bitcoin network compute is the periodic spikes in transaction fees stimulated by the development of the highly irregular ordinals market in 2023–24. Increased institutional demand in 2024 and beyond may also cause upward price pressure given bitcoin's inelastic 21-m supply cap. All of these exogenous factors relating to price uncertainty and global network growth pose significant challenges for bitcoin miners' business planning, thus justifying a wide range of plausible prices from which to

draw samples.

Annual hash revenue is shared between the landfill operator and bitcoin miner. The annual electricity cost for miners was a function of the breakeven cost of producing electricity and the annual power consumption for the fleet of mining rigs. Other revenues and costs were calculated step-wise, with uncertainty from chance variables propagating through the financial performance metrics. Table 2 provides a summary of the model parameters we used.

We also calculated the value of methane mitigation for a landfill capable of generating 10-m kWh/yr (1.14 MW) of electricity. A landfill of that scale would, assuming (1) no parasitic electricity use for landfill operations, (2) 30% power conversion efficiency for LFG to electricity, and an energy content of 10 kWh/m³ of methane, produce a total of 6.67-m m³ of LFG each year, 50% of which would be methane. Further assuming that the landfill was undeveloped, with 100% venting prior to development and methane density of 0.656 kg/m³, this implies that 2187 mt of CH₄ (=61,227 mt of CO₂e at GWP = 28) would be released into the atmosphere annually from the untreated landfill. Given the very distinct temporal patterns of methane emissions from landfills, a function of landfill age, the organic content of waste and other factors, our estimate should be regarded only as an approximation. Emission schedules can be developed following established landfill emission modeling protocols (Alexander et al., 2005).

The US EPA has estimated the social cost of carbon (SCC) and methane (SC-CH₄) (EPA, 2023a). SCC is a function of damage functions, time horizon, and discount rate. In the past, many government projects simply adopted an SCC value of \$20/mt of CO₂e abatement, although many environmental economists argued for values of \$200 or more based on differing opinions about the proper choice of damage functions and discount rates (Pindyck, 2019). The EPA report included a comprehensive review of SCC assumptions and a formal external review process, suggesting SC-CH₄ values of between \$1300 and \$8200/mt (2020 dollars). Given methane's high impact within 30 years, we used the \$4200/mt figure, which adopts a 2% discount rate and time horizon out to 2050.

We also assumed that the mining rigs would be powered by grid electricity in the absence of LFG-based electricity. Note, however, that this would be unlikely, as such a mining facility, in reality, is mobile and could locate anywhere with lower-cost power. We used an estimate of an average carbon intensity of 0.5 g/kWh for grid-sourced electricity. Grid intensity is uncertain due to the many factors influencing it (Scarlat et al., 2022; Williams et al., 2021), so our net benefit estimate should be taken as provisional and only applicable for currently undeveloped landfills.

4. Results

In this section, we present the outcomes of our Monte Carlo simulation, analyzing the financial impact of integrating LFGTE projects with

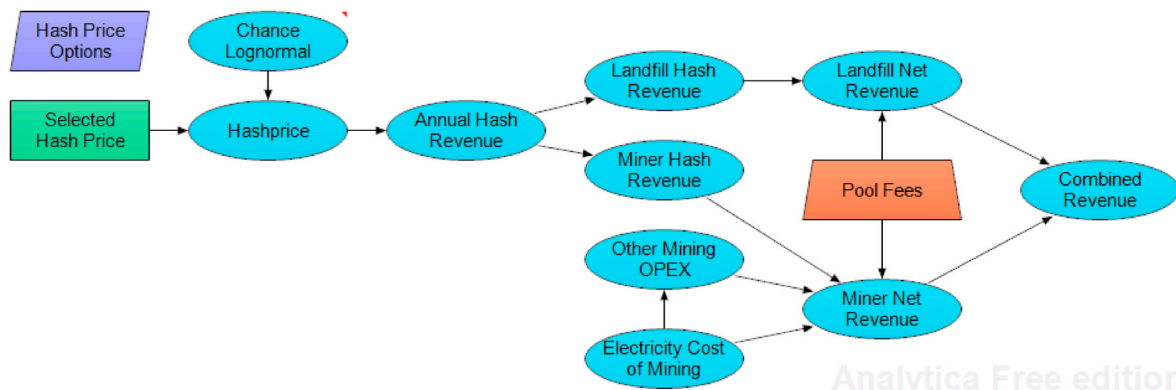


Fig. 3. Relationships between nodes in the financial module.

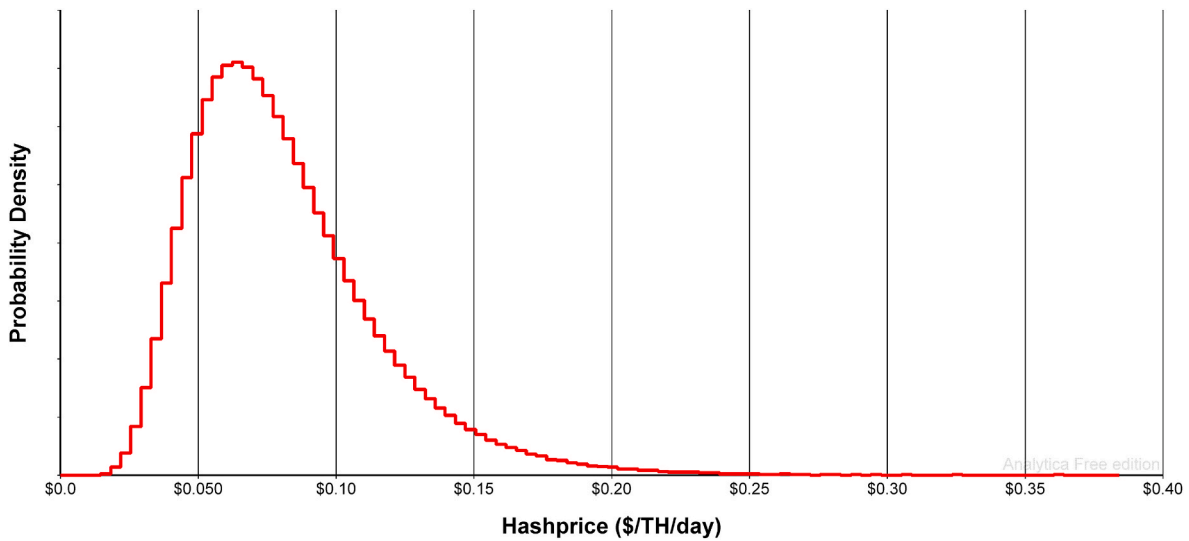


Fig. 4. Lognormal hashprice distribution (min = \$0.0155, median = \$0.075, mean = \$0.081, max = \$0.36/TH/day). Note that we used 100 samples per pdf step; to allow for visual comparison of the trends in financial variables in this and following figures, we do not use a scale on the y-axis.

Table 2
Model parameters and values.

	Type	Notation	Units	Calculation	Value [Range]
Power Use Module					
Selected rigs ^a	Discrete	RIG			S19 XP, S21, S21 hydro
Hash	Discrete	RIGH	TH/s		[151, 200, 335]
Power use	Discrete	RIGP	W		[3247, 3500, 5360]
Cost ^b	Discrete	RIGC	\$		[3473, 5000, 6533]
OPEX proportion	Discrete	OPEX%			[0.15, 0.15, 0.15]
Electricity for mining	Choice	ELEC	kWh/year		10,000,000
Rigs deployed	Variable	DEPLOY	rigs	DEPLOY = ELEC/(24*365*RIGP/1000)	[352, 326, 213]
Electricity Module					
Low breakeven cost	Discrete	BE _L	\$/kWh		[0.01]
High breakeven cost	Discrete	BE _H	\$/kWh		[0.08, 0.09, 0.10, 0.11]
Standard deviation	Variable	STDEV		STDEV=(BE _L + BE _H)/5	[0.014 → 0.036]
Breakeven cost ^c	Chance	c _{be}	\$/kWh	Normal(mean:(BE _L + BE _H)/2; STDEV)	[0.01 → 0.12]
Landfill revenue share	Chance	REV _L		Uniform(0.05, 0.30)	[0.00 → 0.30]
Miner revenue share	Variable	REV _M		REV _M =(1-REV _L)	[0.70 → 1.00]
Financial Module					
Mining pool fees	Constant	POOL			0.02
Hashprice mean ^d	Discrete	HP_AVG	\$/TH/day		[0.050, 0.075, 0.150]
Lognormal transform	Chance	LOGN		Lognormal(mean:1, gsdev:1.5)	[0.206 → 4.843]
Lognormal hashprice	Variable	p _h	\$/TH/day	p _h = HP_AVG*LOGN	[0.016 → 0.363]
Annual hash revenue	Variable	H	\$/year	365*(RIG*RIGH*p _h)	[300,452 → 9,459,709]
Landfill hash revenue	Variable	H _L	\$/year	H _L =H* REV _L	[24,840 → 2,433,155]
Landfill net revenue	Variable	NET _L	\$/year	NET _L = H _L *(H _L *POOL)	[24,343 → 2,384,492]
Miner hash revenue	Variable	H _M	\$/year	H _M =H*REV _M	[267,511 → 7,087,300]
Electricity cost of mining	Variable	EC _M	\$/year	EC _M =c _{be} *ELEC	[100,215 → 999,797]
Other mining OPEX	Variable	OPEX _M	\$/year	OPEX _M = EC _M *OPEX%	[15,032 → 149,969]
Miner net revenue	Variable	NET _M	\$/year	INC _M = H _M *(H _M *POOL)-EC _M -OPEX _M	[(746,794)→6,461,620]
Combined revenue	Variable	REV _{total}	\$/year	REV _{total} = NET _L + NET _M	[(618,452)→8,846,113]

^a Mining rig specs from <https://shop.bitmain.com/> (09 Feb 2024).

^b USD \$ are used throughout this paper.

^c We truncated breakeven price at the lowest (\$0.01) and highest (\$0.10) plausible electricity production cost levels that we considered.

^d The remaining numbers in the Table are based on a lognormally-distributed hashprice with mean p_h = \$0.075 (current hashprice information available at <https://hashrateindex.com/tools/calculator>).

bitcoin mining operations. Our findings highlight the potential revenue streams from bitcoin mining under varying operational and economic conditions. Key results include the comparative revenue performance of different mining rigs, the financial risks and benefits for landfill operators and bitcoin miners, and the significant potential for CO₂e reduction through the proposed integration. These insights are crucial for stakeholders considering the feasibility and impact of leveraging LFGTE for cryptocurrency mining.

4.1. Revenue from bitcoin mining

The annual hash revenue (Fig. 5) is a function of rig hash power, efficiency, and size of the fleet deployed to utilize the full 10-m kWh electricity supply dedicated to mining. Deploying fleets of 326 or 213 more energy-efficient S21 air- or liquid-cooled rigs, respectively, relative to a fleet of 352 less energy-efficient S19j XPs increases the likelihood of higher site revenue, pushing the probability density curve outwards. Recall that total revenue was then split between bitcoin miner

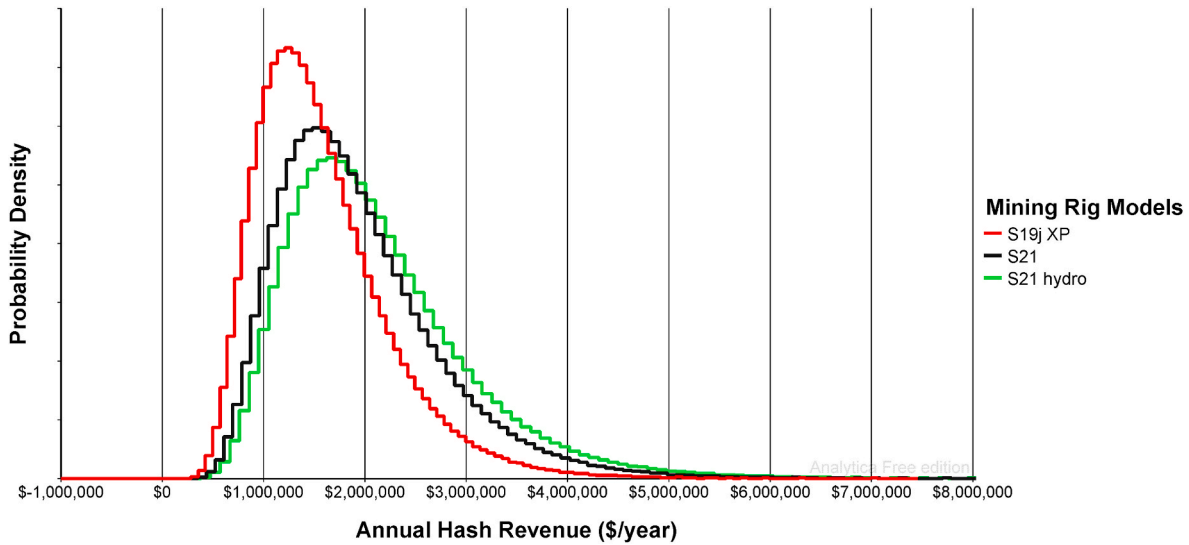


Fig. 5. Total revenue (landfill operator and bitcoin miner) probability distribution for different mining rigs (mean electricity production cost, $c_{be} = \$0.055/\text{kWh}$; mean hashprice, $p_h = \$0.075/\text{TH/day}$). We use a (\$1-m) to \$8-m x-axis to allow for easy visual comparison with later charts for the bitcoin miner.

and landfill operator.

For our baseline model (mean $c_{be} = \$0.055/\text{kWh}$, mean $p_h = \$0.075/\text{TH/day}$), we present summary statistics in Table 3. For our initial review of model performance, we focus only on a fleet comprised entirely of air-cooled S21 rigs: the 326 computers (capital cost of \$1.63-m) fully consume the 10.0-m kWh/year of electricity available.

In our model, the landfill operator does not share in any risks associated relating to the operating costs of mining. As a result, the worst that they could do is have a low level of revenue (Fig. 6).

In our baseline model, the bitcoin miner’s net revenue probability distributions (Fig. 7) show that there are substantial financial risks for the bitcoin miner. Recall, also, that this is a revenue figure and does not account for capital expenditures for rigs and supporting infrastructure.

Combined, the revenue for both the landfill operator and bitcoin miner combined shows positive upside (Fig. 8) but the venture is not without financial risk, even before considering depreciation, which would be approximately in the \$350,000/year range for the mining deployment.

4.2. Factors influencing financial success

In the baseline model, we used random distributions across the full range of plausible parameters but miners might be very unlikely to undertake bitcoin mining under some of those combinations in the real world. For instance, it is very unlikely that commercial miners, given their sensitivity to electricity prices (Carter et al., 2023), would be willing to agree to a 30% revenue share arrangement for an LFGTE project that could, at best, produce electricity at \$0.10/kWh. That would especially be the case if industrial electricity rates from the local grid were only \$0.06/kWh, or if extended bear market conditions and low hashprice was expected over the next two years.

Table 3
Annual financial performance with a fleet of entirely air-cooled S21 bitcoin miners.

Financial result	Minimum	Median	Mean	Maximum	Std Dev
Annual hash revenue, H	\$368,555	\$1,784,850	\$1,937,735	\$8,643,725	\$818,852
Landfill hash revenue, H_L	\$30,470	\$294,211	\$338,433	\$2,223,274	\$208,538
Landfill net revenue, NET_L	\$29,861	\$288,327	\$331,665	\$2,178,809	\$204,367
Miner hash revenue, H_M	\$328,148	\$1,469,343	\$1,599,302	\$6,475,957	\$693,602
Electricity cost of mining, EC_M	\$100,215	\$550,006	\$550,006	\$999,797	\$195,547
Miner net revenue, NET_M	(\$671,799)	\$820,687	\$934,809	\$5,867,640	\$713,652
Combined net revenue, REV_{total}	(\$518,159)	\$1,129,990	\$1,266,473	\$8,046,449	\$830,697

To examine how the financial metrics responded to changes in our parameterizations, we ran additional simulations with different electricity prices and hashprice, alone and combined. To illustrate the breadth of possible outcomes, we report below (Table 4) on alternative scenarios considering all three types of mining rigs, with 27.3% lower landfill electricity generation costs (mean $c_{pe} = \$0.040$, $\sigma = \$0.014$), 100% higher hashprice (mean $p_h = \$0.15/\text{TH/day}$, log-normally distributed), and a combination of both.

Fig. 9 shows the net revenue for bitcoin miners with both a low electricity price and high hashprice. Note that the risk of operation losses from mining are now close to zero, the performance gap between relatively inefficient S19j XP rigs and more efficient S21s has widened, and that there is a long upper tail of the distribution that extends beyond the chart, to >\$15-m/year. Even allowing for depreciation expenses of \$350,000 annually for the mining fleet, mining would typically be highly profitable.

4.3. Emissions mitigation

Based on our use of \$4200/mt for SC-CH4, there would be a gross emissions reduction of 2187 mt CH4, worth \$9.18-m. Based on a grid carbon intensity of 0.5 kg/kWh and SCC value of \$310/mt, using electricity from the grid to power bitcoin mining operations, rather than LFG-generated electricity, would incur a \$1.55-m SCC. The net benefit would thus be \$7.63-m.

The 2023 EPA numbers (EPA, 2023a) are higher than the SCC of \$50/mt value under the Obama administration (Wagner et al., 2021) and in stark contrast to the \$1-\$7/mt figure under the Trump administration (a difference due to the use of higher discount rates). In addition, the SCC values are higher than market prices for carbon credits (<https://carboncredits.com/carbon-prices-today/>), so individual

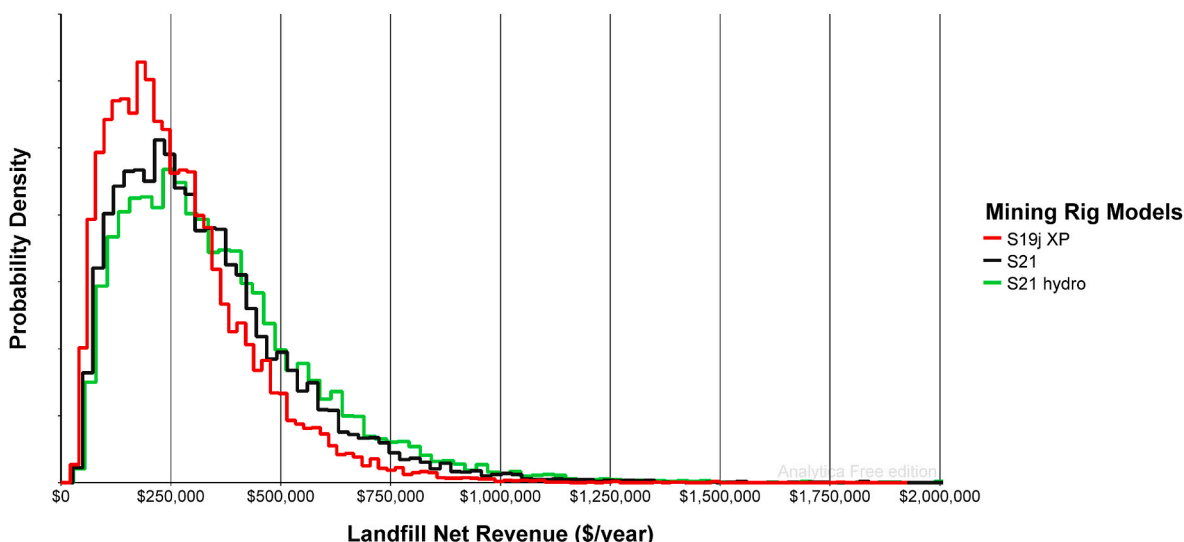


Fig. 6. Landfill operator’s net revenue (mean c_{be} = \$0.055/kWh; mean p_h = \$0.075/TH/day) (note the different x-axis scale relative to other Figures).

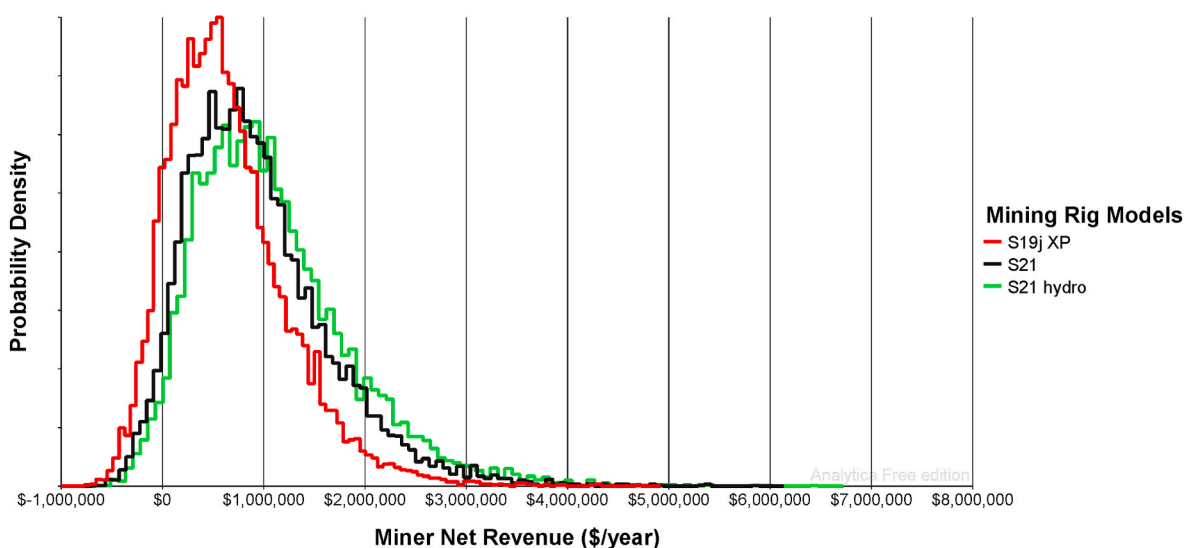


Fig. 7. Bitcoin miner’s net revenue (mean c_{be} = \$0.055/kWh; mean p_h = \$0.075/TH/day).

facilities would need to assess any revenue streams accruing from methane mitigation in accordance with their development status, regulatory environment, and access to mitigation compensation mechanisms.

5. Discussion

In this study, we present a novel model assessing bitcoin mining’s role in mitigating and monetizing methane emissions from LFGTE projects. Centered on the cost dynamics of electricity production from captured LFG, this model highlights the potential economic and environmental benefits of integrating bitcoin mining with methane mitigation efforts at solid waste disposal sites not yet fully utilizing methane capture. This integration not only proposes a method to enhance landfill sustainability but also introduces a potential economic boost for landfill operations currently venting or flaring methane, offering them an alternative revenue source through the global bitcoin market. Such an approach is particularly pertinent in regions where legal mandates require gas flaring, suggesting that bitcoin mining could improve the financial feasibility, potentially accelerating the development of landfill

gas capture infrastructure and reducing the tax burden on local residents and businesses.

However, the model also highlights significant financial risks, particularly for smaller landfills that may have high per-kWh electricity production costs or in situations where the hashprice of mining were to fall even further from its 2022–2024 bear market range. The model highlights the importance of strategic decisions in hardware selection, operational efficiency, and revenue-sharing models to balance benefits and risks for both landfill operators and bitcoin miners.

5.1. Study limitations and future research

Our model simplifies complex phenomena to make the integration of bitcoin mining with LFGTE projects analytically tractable. The global Bitcoin network hash rate and the market price of bitcoin, both pivotal to the model’s economic projections, highlight the importance of understanding risk tolerance in the face of financial uncertainties inherent in mining and landfill operations. These factors are notoriously hard to predict. As such, our results should not be viewed so much as a predictive model of what financial status will be in the future. Rather, this

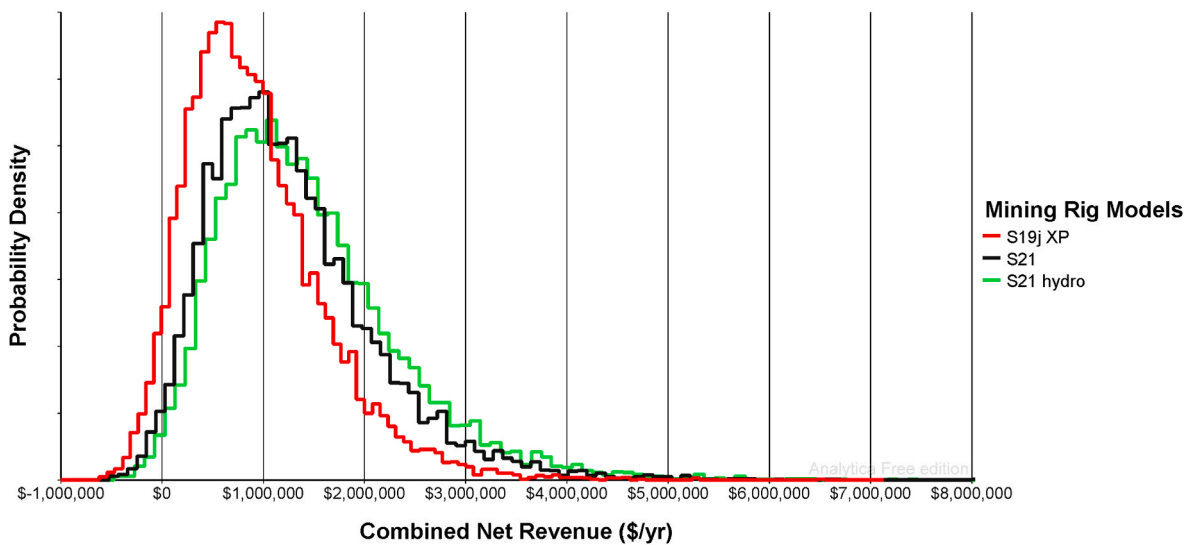


Fig. 8. Revenue less operating and pool expenses for the landfill operator and bitcoin miner combined (mean c_{be} = \$0.055/kWh; mean p_h = \$0.075/TH/day).

Table 4

The influence of varying mining rigs, breakeven electricity cost (c_{be}), and hashprice (p_h) on bitcoin mining gross profit ($n = 10,000$ sample size).

Scenario	Metric	Rig	Minimum	Median	Mean	Maximum	Std Dev
1. Original							
Mean c_{be} = \$0.055	Landfill net revenue	S19j XP	\$24,343	\$235,048	\$270,378	\$1,776,197	\$166,603
	Landfill net revenue	S21	\$29,861	\$288,327	\$331,665	\$2,178,809	\$204,367
	Landfill net revenue	S21 hydro	\$32,679	\$315,546	\$362,974	\$2,384,492	\$223,660
Mean p_h = \$0.075	Miner net revenue	S19j XP	(\$746,794)	\$556,856	\$645,192	\$4,704,963	\$595,762
	Miner net revenue	S21	(\$671,799)	\$820,687	\$934,809	\$5,867,640	\$713,652
	Miner net revenue	S21 hydro	(\$633,487)	\$955,032	\$1,082,766	\$6,461,620	\$774,815
2. Low c_{be}, original p_h							
Mean c_{be} = \$0.040 (-27.3%)	Landfill net revenue	S19j XP	\$24,343	\$235,048	\$270,378	\$1,776,197	\$166,603
	Landfill net revenue	S21	\$29,861	\$288,327	\$331,665	\$2,178,809	\$204,367
	Landfill net revenue	S21 hydro	\$32,679	\$315,546	\$362,974	\$2,384,492	\$223,660
Mean p_h = \$0.075 (0%)	Miner net revenue	S19j XP	(\$433,878)	\$722,261	\$817,694	\$4,816,773	\$574,235
	Miner net revenue	S21	(\$358,883)	\$986,881	\$1,107,311	\$5,979,450	\$695,916
	Miner net revenue	S21 hydro	(\$320,571)	\$1,122,056	\$1,255,268	\$6,573,430	\$758,573
2. Original c_{be}, high p_h							
Mean c_{be} = \$0.055 (0%)	Landfill net revenue	S19j XP	\$53,707	\$474,309	\$541,697	\$2,776,778	\$334,386
	Landfill net revenue	S21	\$65,880	\$581,821	\$664,484	\$3,406,192	\$410,181
	Landfill net revenue	S21 hydro	\$72,099	\$636,745	\$727,212	\$3,727,743	\$448,903
Mean p_h = \$0.150 (+100%)	Miner net revenue	S19j XP	(\$442,606)	\$1,720,813	\$1,921,949	\$11,304,354	\$1,126,332
	Miner net revenue	S21	(\$293,677)	\$2,243,925	\$2,500,970	\$13,979,471	\$1,372,926
	Miner net revenue	S21 hydro	(\$227,266)	\$2,513,500	\$2,796,776	\$15,346,116	\$1,499,434
4. Low c_{be}, high p_h							
Mean c_{be} = \$0.040(-27.3%)	Landfill net revenue	S19j XP	\$53,707	\$474,309	\$541,697	\$2,776,778	\$334,386
	Landfill net revenue	S21	\$65,880	\$581,821	\$664,484	\$3,406,192	\$410,181
	Landfill net revenue	S21 hydro	\$72,099	\$636,745	\$727,212	\$3,727,743	\$448,903
Mean p_h = \$0.150 (+100%)	Miner net revenue	S19j XP	(\$140,657)	\$1,882,923	\$2,094,451	\$11,437,770	\$1,115,508
	Miner net revenue	S21	(\$10,661)	\$2,408,275	\$2,673,472	\$14,112,887	\$1,364,205
	Miner net revenue	S21 hydro	\$55,750	\$2,677,262	\$2,969,278	\$15,479,532	\$1,491,521

type of modeling, where variables with a high level of uncertainty are recognized as such, gives miners and landfill operators an idea of what they need to believe about exogenous factors affecting hashprice in order to proceed with mining. This approach is characteristic of models dealing with deep uncertainty (Bankes, 1993; Lempert et al., 2004).

The model’s current parameterizations, reflecting typical North American landfill conditions, may not directly apply to varied geographic and operational contexts, particularly in developing countries with different climate, waste composition, and management practices. Despite this, its flexible design allows for recalibration to diverse scenarios, indicating broad applicability with potential adjustments for local specifics.

Limitations also stem from simplified assumptions about revenue-sharing and electricity costs, which lack the complexity of real-world PPAs and negotiated revenue-sharing arrangements. Such agreements,

influenced by regulatory, market, and strategic factors, suggest our model’s financial flow and risk distribution may not capture the full nuance of actual implementations. Our assumption that the bitcoin miner pays all capital and operational costs, taking on all risks, may not be appropriate for larger landfills that already have the capacity and management expertise to produce biofuel and generate electricity. In such cases, revenue sharing agreements may need to reward risk-taking landfill operators with higher bitcoin revenue shares.

Future research should address these limitations by examining the impact of technological advancements in bitcoin mining and changes in regulatory frameworks on the integration’s viability. Innovations in mining hardware, shifts in energy policy, and new incentives for renewable energy could significantly affect the model’s assumptions and outcomes. Enhancing our model to reflect these dynamic factors will deepen our understanding of how digital financial technologies intersect

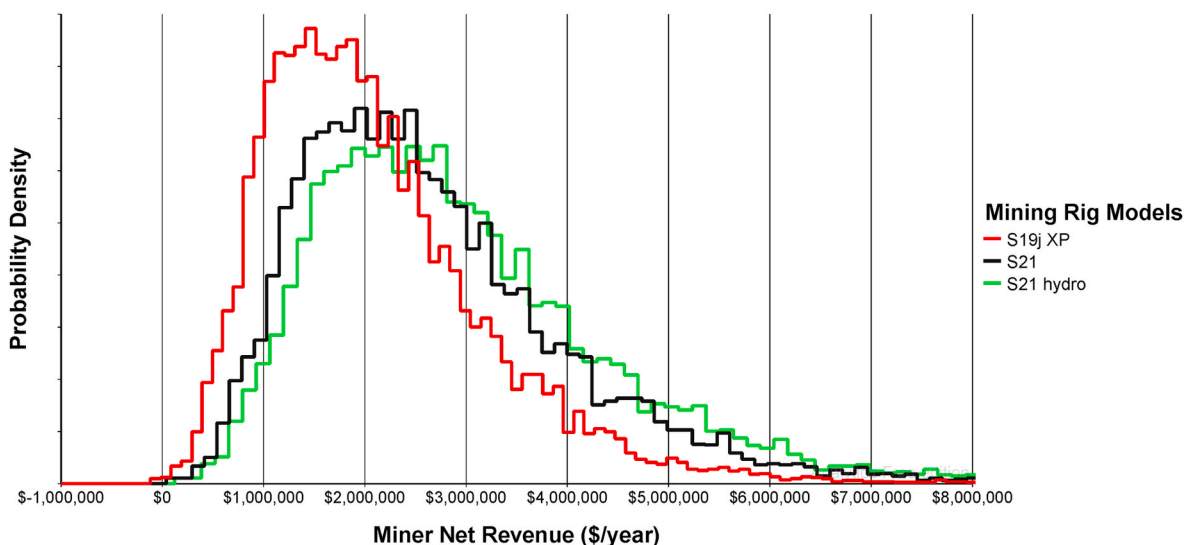


Fig. 9. Miner net revenue with both lower electricity and higher hashrate prices (mean c_{be} = \$0.040/kWh; mean p_h = \$0.150/TH/day).

with renewable energy projects, providing insights into effective strategies for leveraging bitcoin mining in methane mitigation efforts.

5.2. Determinants of financial viability

The model clearly demonstrates that lower electricity prices, achievable through efficient LFGTE operations, significantly enhance the financial outlook for bitcoin miners by reducing the risk of operational losses. For instance, simulations within our study showed a direct correlation between electricity cost reductions and profitability improvements for mining operations. This underscores the necessity of securing competitive energy sources as a cornerstone for sustainable mining practices. Conversely, the model revealed stark variability in financial performance, with net revenues for miners ranging from as low as (\$442,606) to as high as \$15,479,532 annually, depending on revenue sharing and electricity production costs.

For smaller landfills, the model suggests that leveraging low electricity costs and exploring diversified revenue streams may be essential strategies to attract commercial mining partners. This could involve innovative business models and revenue sharing arrangements tailored to align stakeholder interests, thereby fostering mutually beneficial partnerships. These strategies not only aim to align stakeholder interests but also to capitalize on the unique opportunities presented by the bitcoin mining market.

Moreover, hashprice fluctuations emerge as a significant determinant of financial outcomes, with scenarios of increased hashprice – either alone or in conjunction with lower electricity costs – substantially boosting revenue potential. This finding points to the decisive impact of bitcoin market conditions on the economic feasibility of integrating mining with LFGTE projects. The pronounced variability in hashprice, a primary driver of profitability variations, underscores the critical need for business models that are both adaptive and flexible, capable of navigating the bitcoin mining sector's volatile economic landscape.

Incorporating the unique capacity of bitcoin mining to utilize electricity generated from LFGTE projects presents a substantial opportunity for CO₂e reduction, demonstrating a significant dual benefit for both environmental sustainability and economic viability. Our model's findings, illustrating how a relatively small landfill could mitigate 2187 mt of methane, underscore the importance of integrating bitcoin mining with LFGTE processes. In cases where that benefit can, via carbon credits, be financially captured by landfill operators, landfills can increase their level of cost recovery and reduce financial burdens on governments and taxpayers.

5.3. Technological advancements and energy efficiency in mining hardware

Our analysis reveals that selecting modern, energy-efficient mining rigs significantly improves the financial outlook for integrating bitcoin mining with LFGTE projects. These advanced rigs not only enhance the potential for higher gross profits but also act as a critical buffer against financial losses. Specifically, simulations from our study demonstrate that energy-efficient technology expands the probability distributions of financial outcomes, increasing the likelihood of positive performance. Such findings underscore the importance of hardware efficiency in mitigating the risks associated with the volatile nature of bitcoin mining and fluctuating energy costs.

Adopting more efficient hardware shifts the economic equation of landfill-mining integrations towards greater resilience against market fluctuations. As a result, the scalability of mining operations, underpinned by technological progress and the strategic deployment of efficient hardware, becomes essential. This shift demands a reassessment of financial models to accurately reflect the interplay between energy efficiency, operational costs, and market-driven revenue potentials.

Future research might delve into the scalability of bitcoin mining concerning energy availability and technological advancements. Investigating the impact of the latest mining rigs on optimizing energy consumption and financial outcomes, especially within diverse regulatory frameworks, is crucial. Anticipated regulatory changes aiming to foster renewable energy use and efficiency in bitcoin mining will likely influence the economic feasibility of these integrations.

5.4. Carbon credits

The pursuit of carbon credits offers a financial incentive primarily for landfills that do not yet destroy destruction or monetize emissions reductions, specifically those venting significant methane. Installing Gas Collection and Control Systems (GCCS) becomes an additional but critical investment, facilitating methane capture for power generation and bitcoin mining.

The complexity of royalty-based contracts for landfill gas is notable, encompassing all revenues generated by the LFGTE developer, including carbon credits and other environmental attributes. Such arrangements offer flexibility to customize agreements concerning carbon credits, thus mitigating payback risks associated with GCCS investments, particularly given the landfill's compliance obligations for methane collection and destruction.

Revenue from carbon credits, beyond the share allocated to the landfill, is typically divided between the bitcoin mining operation and the infrastructure financing provider. During the refinancing period of the infrastructure loan, the majority of carbon credit revenue tends to favor the financing provider. Subsequently, the lion's share of this revenue shifts to the bitcoin mining company, reflecting a structured transition in revenue allocation over time.

The role of independent specialists in the Measurement, Reporting, and Verification (MRV) of carbon credits is crucial. These specialists are compensated based on the volume of carbon credits generated, emphasizing the importance of accurate and reliable verification processes in the monetization of methane mitigation efforts.

5.5. Scalability and global methane mitigation initiatives

The integration of LFGTE operations with bitcoin mining may hold potential for environmental management and energy production on a global scale. The scalability of such initiatives closely links to the dynamics of the global bitcoin market and the availability of low-cost, waste and renewable energy sources. In the USA alone, there were some 62 underdeveloped low-flow (400–1200 SCFM) solid waste disposal sites and a total of 463 LMOP candidate sites with 965 MW capacity in aggregate, and 53-m mt/year CO₂e abatement potential (<https://www.epa.gov/lmop/project-and-landfill-data-state>, July 2023 data). A total of 532 projects with 1287 MW capacity are already active and actively mitigating methane emissions. While bitcoin mining at already-developed landfills may not accrue any benefits in terms of net mitigation, improving the economics of LFGTE operations may bolster the long-term sustainability of facilities and reduce waste disposal costs or taxation rates for local citizens and businesses.

The economic feasibility of integrating LFGTE with bitcoin mining in developed countries, however, faces challenges from alternative low-cost, renewable energy sources and stringent regulatory frameworks. The effectiveness of market signals to incentivize such integration significantly depends on the global bitcoin market's evolution and available energy sources. For instance, mining at small LFGTE operations in countries with robust regulations may not be economically viable if miners have access to other low-cost energy sources. Nevertheless, LFGTE operations could significantly benefit from improved cost recovery while aligning with regulatory standards.

Expanding mitigation options and broadening geographic scope beyond current carbon mitigation agreement signatories is crucial (Malley et al., 2023). Global landfills emit significant methane from approximately 2-b mt of solid waste generated annually—a figure projected to increase by 70% by 2050 (Kaza et al., 2018). Saunois et al. (2020) estimated that annual methane emissions specifically from waste disposal (landfills and wastewater treatment) were in the order of 65-m mt, accounting for about 12% of global anthropogenic emissions.

National emissions from landfills in China and India were estimated at 1.86-m mt (Du et al., 2017) and 1.08-m mt (Singh et al., 2018), respectively. In Africa, where urban areas produce approximately 244-m mt of waste annually, the potential for energy recovery and electricity generation is vast, yet often hindered by economic and management challenges (Scarlat et al., 2015). If this resource could be tapped, it would theoretically be possible to recover as much as 363 PJ of energy and generate 122.2 TWh of electricity annually. For context, the global Bitcoin network currently (24 Feb 2024) has an annualized electricity consumption of 165.7 TWh.

Nisbet et al. (2020: 27) note that “in many tropical nations, landfill methane emissions are wholly uncontrolled and are characteristically high ... [and that] there is often little interest in investment in methane emission control and there is poor management of the emissions in many cases.” Small scale biogas electricity in Africa, for example, has been economically marginal, often relying on subsidies or feed-in-tariff rates of up to \$0.20/kWh to maintain operation (Kabeyi and Olanrewaju, 2022). Introducing bitcoin mining as a viable energy consumer near

under-utilized, low-cost energy sources could offer significant benefits, including spin-off local community electrification through excess energy distribution, a phenomenon already observed in Africa (Hallinan et al., 2023).

5.6. Application of this modeling approach in other sectors

Methane emissions from livestock farming is a major source of methane emissions (Saunois et al., 2020), largely due to enteric fermentation in ruminants and manure management practices. For example, farm manure has the potential to supply about 1% of the US's annual energy consumption (Cuéllar and Webber, 2008). With electricity production costs in the food sector ranging from \$0.05 to \$0.12/kWh (Camarillo et al., 2012), integrating bitcoin mining could offer a viable path to monetizing energy otherwise lost to emissions. In India's Haryana state alone, dung production could generate 9.84 TWh annually (Nehra and Jain, 2023), roughly 6% of the current Bitcoin network's global power needs, showcasing the sector's potential contribution to sustainable energy production and emission reduction.

Urban wastewater treatment facilities, through anaerobic digestion of sewage sludge (Shen et al., 2015), also stand as significant methane emitters (Saunois et al., 2020; Tong et al., 2024). However, these facilities typically have mechanisms for biogas capture and use, mainly for heating or electricity generation (Shen et al., 2015). By incorporating bitcoin mining, such plants could significantly lower their net operational costs. Given that urban WWTPs often have more diverse options for biogas and electricity sales than rural landfills, the introduction of bitcoin mining needs to be evaluated against potential opportunity costs to determine its financial and environmental return on investment. The question become one of determining under which circumstances bitcoin mining could contribute to mitigation performance while reducing financial burdens associated with operating urban WWTPs.

Similarly, vented methane from oil and gas production presents an untapped resource for bitcoin mining (Lorenzato et al., 2022). Integrating mining operations with methane capture initiatives in this sector could not only provide a new revenue stream but also aid in significantly reducing greenhouse gas emissions. The broad potential of our model to assess bitcoin mining integration across these sectors highlights its capacity to identify opportunities to leverage bitcoin mining's economic incentives for enhanced methane capture and utilization.

6. Conclusions

This study underscores the transformative potential of bitcoin mining to convert waste gas from LFGTE projects into a valuable resource, shifting from traditional regulation-driven environmental mitigation to innovative, financially incentivized efforts. By leveraging bitcoin's economic incentives, our framework proposes a method to expedite methane mitigation, enhance the economic appeal of these initiatives, and potentially reduce the tax burden associated with regulatory compliance. This approach challenges conventional strategies and introduce a scalable solution for methane reduction, minimizing reliance on government subsidies or infrastructure spending.

Integrating renewable energy projects with Bitcoin mining suggests a novel pathway for accelerating infrastructure development and simplifying regulatory compliance, presenting a fresh perspective on sustainable energy. This market-oriented strategy highlights Bitcoin mining's potential to scale methane mitigation efforts effectively and suggests its applicability in sectors facing similar challenges.

Given the complexity of landfill methane reduction, no single strategy suffices (Hoy et al., 2023). Success in global methane mitigation targets requires deploying existing technologies alongside innovative solutions and supportive policies. Our results emphasize the importance of using plausible assumptions about Bitcoin hash price and electricity generation potential to assess the viability of bitcoin mining as a mitigation strategy, prompting the question: “What must we believe about

bitcoin hashprice and landfill electricity generation costs to make bitcoin mining a viable mitigation option?"

Future research could focus on several key areas to further explore the potential of integrating Bitcoin mining with LFGTE projects. Conducting a comprehensive Life Cycle Assessment (LCA) of these systems would provide valuable insights into their environmental impacts and sustainability (e.g., Köhler and Pizzol, 2019, who conducted a general Bitcoin mining LCA). Additionally, examining the scalability of such integrations in diverse geographic and economic contexts, especially in developing countries, could enhance their global applicability. Further exploration into advancements in ASIC technology and energy efficiency may reveal how innovations could influence economic viability and environmental outcomes. Finally, understanding evolving regulatory and policy landscapes and tools across jurisdictions (Capano and Howlett, 2020) will be crucial in determining how government policies can either support or hinder the integration of Bitcoin mining with renewable energy projects.

In conclusion, Bitcoin mining provides a market-based approach to methane mitigation that does not require government subsidies. By leveraging the economic incentives inherent in Bitcoin mining, this model offers a compelling solution for methane reduction and sets the stage for future applications in various sectors, highlighting its potential to help drive sustainable energy transitions worldwide.

CRediT authorship contribution statement

Murray A. Rudd: Writing – review & editing, Writing – original draft, Validation, Methodology, Investigation, Formal analysis, Conceptualization. **Matthew Jones:** Writing – review & editing, Validation. **Daniel Sechrest:** Writing – review & editing, Validation. **Daniel Batten:** Writing – review & editing, Validation. **Dennis Porter:** Writing – review & editing, Validation, Project administration.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Murray A Rudd reports a relationship with Satoshi Action Education that includes: consulting or advisory. Dennis Porter reports a relationship with Satoshi Action Education that includes: board membership and employment. Matthew Jones reports a relationship with Nodal Power, Inc. that includes: employment and equity or stocks. Daniel Sechrest reports a relationship with Nodal Power, Inc. that includes: employment and equity or stocks. Daniel Batten reports a relationship with CH4 Capital that includes: equity or stocks. All authors work with organizations active in the Bitcoin space. MAR and DP work for a 501(c)(3) nonprofit, MJ and DS for a commercial firm actively using landfill gas emissions for Bitcoin mining, and DB for a venture capital fund actively raising funds for international landfill methane mining operations. This project was funded from nonprofit general operations. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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