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Research Article

From Mining to Mitigation: How Bitcoin Can Support Renewable Energy Development and Climate Action

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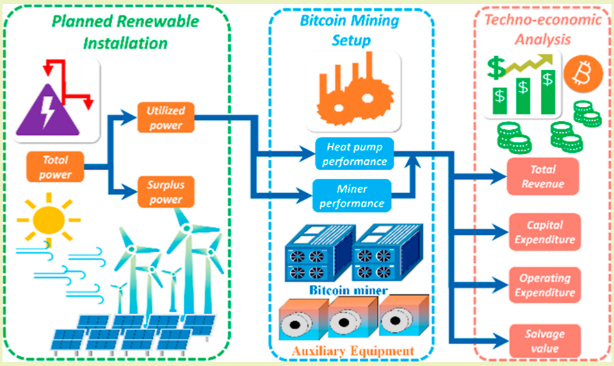
ABSTRACT: The world is currently facing a major issue of high emissions from fossil-fuel-based energy sources, which contribute to the persistent problem of climate change. A switch to a renewable-powered infrastructure is necessary to mitigate this challenge. However, the shift to renewable energy faces obstacles, such as high costs and economic uncertainties. This work proposes mitigation of climate change by investigating the potential for bitcoin mining to serve as a means of utilizing surplus renewable energy from planned installations before grid integration. The study's findings indicate the potential for bitcoin to provide economic benefits as an alternative to grid-powered mining at planned renewable installations across the U.S. states. We show that states like Texas have the maximum potential, with 32 planned renewable installations that could generate combined profits of $47M using bitcoin mining during precommercial operation.



KEYWORDS: *renewable energy, climate change, blockchain, bitcoin, energy transition, cryptocurrency*

■ INTRODUCTION

On January 3, 2009, Nakamoto introduced bitcoin as a revolutionary new way to facilitate online payments, eradicating the need for third-party financial institutions.[1] Little did the world know at the time that this new technology would significantly transform how people experience payments, monetization, and exchange of tokens. Apart from its role in the financial sector, the past decade has shown that adopting blockchain-based applications can transform different aspects of our lives. As an illustration, in the energy sector, blockchain holds the potential to ensure the privacy and security of energy distribution operations.[2] It would decrease the costs of interconnecting distributed energy resources in the decentralized network paradigm[3] and support the climate actions.[4] In the healthcare industry, blockchain technology offers a superior data storage system for vaccination records that would be anonymous, entrenched, and transparent.[5] Blockchain technology can also play a vital role in bolstering food security by assigning unique digital identifiers to food items, enabling precise tracking of their location, condition, and growth stages.[6] It is also considered that blockchain can assist in human rights investigations as it could establish a chain of custody for scientific evidence, which is essential in human rights cases.[7] To appreciate the scale of the cryptocurrency industry's expansion, it is worth noting that on February 21, 2021, the market capitalization of bitcoin was $1.08 trillion—a figure that exceeds the gross domestic product (GDP) of several countries, including The Netherlands, Saudi Arabia, Turkey, and Switzerland.[8] Despite recent events that have impacted its market capitalization, it is crucial to recognize the economic potential of an industry that has demonstrated resilience and continues to bounce back after every setback.[9,10] Even with the reduction in miner rewards, every 4 years,[11,19] million bitcoins have already been mined, with more to follow after regular intervals, depicting that blockchain applications like bitcoin have gone from strength to strength.[12] It is a conservative, if not an optimistic, approach to consider how such technology could still shape various aspects of our lives toward a sustainable and climate-friendly future.

While blockchain continues to make strides in various aspects of our society, the world is also facing the critical

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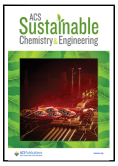

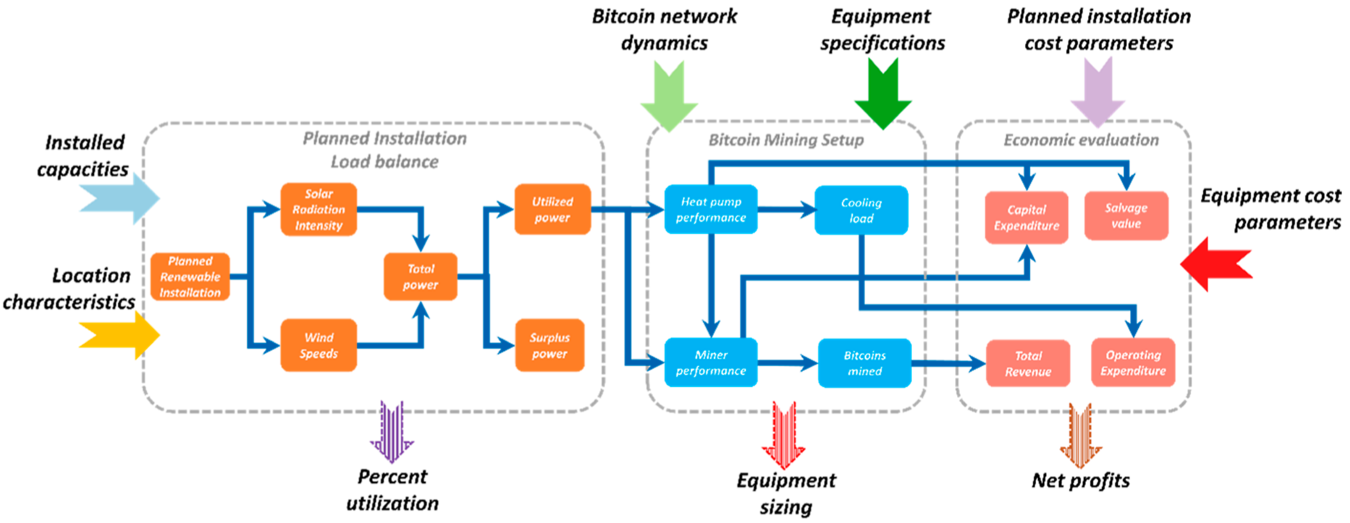

Figure 1. Methodology used to examine the feasibility of bitcoin mining to utilize excess renewable energy from planned installations before integrating with the grid. The blue arrows in the inner boxes show the computation steps.

challenge of climate change. Despite the Paris Agreement that brought 196 countries to the table to collectively fight this glooming climate change problem,[13] it is evident that we are falling behind our climate agreement targets which restrict the global temperature rise to 2 °C by 2100, as indicated by previous studies.[14,15] In the fight against climate change, countries such as the U.S., China, and Germany are investing in renewable energy infrastructure to replace conventional power sources.[16−20] To reduce carbon emissions and facilitate the transition toward a more sustainable energy matrix, many countries incentivize renewable energy production.[21−23] However, the anticipated growth of renewable energy capacity is hindered by factors such as high capital expenditure and the intermittent nature of renewable energy sources. Moreover, the lack of suitable energy storage options leads to significant renewable energy curtailments.[24] To reduce economic risks for investors and support renewable installations, governments must implement specific policies, incentives, and risk mitigation strategies.[25] Prior to integration with the grid, a given renewable energy installation is capable of producing power below its nameplate capacity yet generates no revenue.

In the past, the growing popularity of blockchain technology, particularly grid-powered cryptocurrencies, such as bitcoin, has had a negative impact on the battle against climate change. Bitcoin mining has been heavily criticized for its exorbitantly high energy consumption and resulting carbon footprint.[26−29] In contrast to criticism that views it as a contributor to global carbon debt, this study examines whether crypto operations such as bitcoin mining can serve as a catalyst to improve the economic competitiveness of planned renewable installations in the U.S. As a result, it can aid in transitioning toward cleaner energy infrastructure and mitigating climate change. We conduct a prospective investigation and analysis to explore the potential of crypto operations to enhance the economic benefits of planned solar and wind installations in various US states.

■ METHODS

As illustrated in Figure 1, suitable data sources are essential for assessing the viability of using Bitcoin to extract the added profitability from planned renewable installations during the precommercial operation. The energy produced by wind turbines relies on the incoming wind velocity and crucial aspects of the turbine, such as the minimum and maximum operational speeds. In the case of solar photovoltaic (PV) systems that transform incoming solar radiation into energy, the total power available at different time intervals depends on the incident radiation, solar panel efficiency, and solar power capacity. The National Renewable Energy Laboratory's System Advisor Model and the Visual Crossing Weather API have been employed to obtain hourly solar radiation intensities and wind speeds, respectively, which are then used to determine the available power from different planned renewable source installations.[30,31] In the crypto industry, a computer designed to address complex mathematical problems in return for a reward in terms of a cryptocurrency is called a miner.[32] In this study, Bitmain Antiminer S19j Pro was the miner considered with its respective hashing power and power consumption.[33] Another vital data source in this work corresponds to the network dynamics associated with bitcoin transactions. These network dynamics mainly consist of bitcoin prices and network difficulty levels acquired from the available mining databases.[34] Other critical input parameters in this work, such as equipment specifications, have been obtained from previous literature.[35−39]

The proposed model formulation in this work aims to maximize profitability (profit) using bitcoin mining based on the available power from the planned renewable installations before grid integration. We formulate the following models to maximize the net profit during the operation of the facility for bitcoin mining:

max profit
s.t. load balance constraints given in eqs 1−5
operational constraints given in eqs 6−9
economic evaluation constraints given in eqs 10−19

The load balance constraints employ the data for wind speed and solar irradiation for different planned renewable installations considered in the study. The wind or solar power values that are calculated represent the total available power that must be divided between the utilized and surplus power at different time intervals. These constraints also include the distribution of the utilized power between the mining equipment and the auxiliary equipment for the bitcoin mining setup. Operational constraints used in the study govern the equipment performances, including the number of bitcoins mined, energy utilization levels, cooling loads, and so forth. For instance, the cooling load requirement for miners is proportional to the power consumption, which must be removed using auxiliary heat pumps. Similarly, the specified coefficient of performance for heat pumps determines their power consumption. The operational constraints also outline the upper and lower limits of the power assigned to each piece of equipment, considering the number of units in use and their individual capacities. The economic analysis in the study requires the determination of the income generated over various time periods, the cost of capital investments, operating expenses, and the residual value of the equipment used in the project. The revenue generated from the bitcoin mining process depends on the bitcoin price, the number of bitcoins rewarded on adding a new block, the hash rate, the mining time, and the present network difficulty. Mining difficulty indicates how difficult it is to confirm a transaction in the network and, thus, add a block to the blockchain to get bitcoin as the reward. The capital expenditure is determined by using the unit capital costs and the number of units used in the project life. The operating cost for the process components is estimated by summing the operational and maintenance cost units in different time intervals.[23] Lastly, the double-depreciation method was used to calculate the salvage value for the equipment used.

Optimization Modeling Framework. We utilize the data for wind speed and solar irradiation for different planned renewable installations at varying capacities to obtain the total available power. In the case of wind energy systems, the power generated by wind turbines depends on the incident wind speed. Moreover, the wind turbine characteristics are crucial in power generation, including the cut-in and cut-out speed (m/s). In this study, we utilize a piecewise linear equation to estimate the wind turbine output power as a function of incident wind speed, as shown in the equation below[38]

$$\mathrm{Pwind}_t = \begin{cases} \mathrm{Pr} & v_\mathrm{r} < v_t^\mathrm{s} < v_\mathrm{cout} \\ \mathrm{Pr}\cdot\dfrac{v_t^\mathrm{s} - v_\mathrm{cin}}{v_\mathrm{r} - v_\mathrm{cin}} & v_\mathrm{cin} < v_t^\mathrm{s} < v_\mathrm{r}, \qquad \forall\, t \in T \\ 0 & \text{otherwise} \end{cases} \tag{1}$$

where Pwind_t is the wind power output at time interval t, and T defines the total time interval for the project life. Pr is the rated output of the wind turbine. v_r, v_cin, and v_cout are the rated wind speed and the cut-in and cut-out wind speed, respectively.[40] In the context of wind power generation, the cut-in speed refers to the minimum wind velocity at which the turbine generates power; any wind speed below this threshold lacks the force to rotate the blades. The rated wind speed indicates the point at which the turbine achieves its designated power output capacity. Beyond this speed, the power output remained fairly constant. On the other hand, the cut-out speed is the maximum wind speed for turbine operation to avert potential damages. v_t^s is the wind speed at any given location for a planned renewable installation at time t. In the case of a solar PV planned installation, which converts solar radiation into power, the total power available at a given time depends on incident radiation, the solar panel efficiency, and the surface area of collector panels. It can be represented as a linear function as shown below[38]

$$\mathrm{Psolar}_t = \mu^\mathrm{PV}\cdot\mathrm{rsolar}_t\cdot S^\mathrm{PV}, \qquad \forall\, t \in T \tag{2}$$

where Psolar_t is the output PV power, μ^PV is the solar panel efficiency, indicating the proportion of incoming energy that a solar panel can convert into usable electrical energy,[41] and rsolar_t is the incident solar irradiation. The load balance for the available power (P_t^AVAIL) from a given planned renewable installation which must be distributed among the components of utilized power (P_t^UTL) and surplus power (P_t^Surplus) in different time intervals, can be described using the following equation

$$P_t^\mathrm{AVAIL} = P_t^\mathrm{UTL} + P_t^\mathrm{Surplus} \tag{3}$$

While the load balance for the total power remains the same with two components, i.e., utilized power and surplus power, as described in eq 3, the load balance for the utilized power in bitcoin mining can be described as follows

$$P_t^\mathrm{UTL} = P_t^\mathrm{Miner} + P_t^\mathrm{HP} \tag{4}$$

where P_t^Miner and P_t^HP refer to the power dedicated to the bitcoin mining equipment and the auxiliary heat pumps in different time intervals. Equation 5 calculates the total utilization (UTL) for the available power as shown below

$$\mathrm{UTL} = \frac{\sum_{t\in T} P_t^\mathrm{UTL}}{\sum_{t\in T} P_t^\mathrm{AVAIL}} \tag{5}$$

However, the total power used for bitcoin mining in each time interval must be less than the mining equipment's cumulative power capacity. Therefore, using N^Miner as the number of mining equipment along with $P_\mathrm{MAX}^\mathrm{Miner}$ and $P_\mathrm{MIN}^\mathrm{Miner}$ being the limits on the power consumption of individual mining equipment, eq 6 defines the limits to the power dedicated toward the bitcoin mining equipment.

$$N^\mathrm{Miner}\cdot P_\mathrm{MIN}^\mathrm{Miner} \le P_t^\mathrm{Miner} \le N^\mathrm{Miner}\cdot P_\mathrm{MAX}^\mathrm{Miner} \tag{6}$$

The total heat that must be removed from the mining equipment (P_t^heat) can be calculated using the total power consumed by the mining equipment and the associated factor (hf) as follows

$$P_t^\mathrm{heat} = P_t^\mathrm{Miner}\cdot\mathrm{hf} \tag{7}$$

Considering the coefficient of performance (COP) for the heat pumps, which represents the ratio of useful heat output to the energy input required to achieve that heat transfer,[42] eq 8 calculates the total power consumed by this auxiliary equipment (P_t^HP).

$$P_t^\mathrm{heat} = P_t^\mathrm{HP}\cdot\mathrm{COP} \tag{8}$$

However, based on the number of heat pumps utilized (N^HP), there are limits to the total power consumed in heat pumps based on the individual capacities of the pumps, as described in the following equation

$$N^\mathrm{HP}\cdot P_\mathrm{MIN}^\mathrm{HP} \le P_t^\mathrm{HP} \le N^\mathrm{HP}\cdot P_\mathrm{MAX}^\mathrm{HP} \tag{9}$$

where $P_\mathrm{MAX}^\mathrm{HP}$ and $P_\mathrm{MIN}^\mathrm{HP}$ refer to the heat pump's maximum and minimum power consumption, respectively. The profit calculation is based on the revenue generated for the entire life span of the project and the associated costs during this period. The total revenue for the project (REVENUE) can be calculated as the summation of the revenue generated at the hourly resolution scale considered in the study, represented as follows

$$\mathrm{REVENUE} = \sum_{t\in T} \mathrm{rev}_t \tag{10}$$

where rev_t denotes the revenue generated in various time intervals using the mined bitcoin. We utilize eq 11 to calculate the revenue from bitcoin mining in different time intervals.[25,32] The calculation of revenue from bitcoin mining depends on several factors. The market price of bitcoin ($\mathrm{SP}_t^\mathrm{BIT}$) sets the selling value of each mined coin. Meanwhile, the network difficulty (D_t) represents how hard it is to mine a new block in the blockchain.[43] As miners join the network or as more hashing power is added to the system, the difficulty in ensuring the rate of block generation remains consistent. The hashing power (H_t) indicates the computational capability of the mining equipment to determine the speed and efficiency of bitcoin mining.[44] The block reward (R) is used to calculate the number of bitcoins awarded for mining a new block,[45] while the length of the mining time interval (t_m) then defines the period over which this revenue is earned. Lastly, the constant 2^{32} is the expected number of hashes to find a valid block.[25]

$$\mathrm{rev}_t = \frac{\mathrm{SP}_t^\mathrm{BIT}\cdot R\cdot H_t\cdot t_\mathrm{m}}{D_t\cdot 2^{32}} \tag{11}$$

The capital expenditure for the mining equipment (C^Miner) and the heat pumps (C^HP) can be calculated using the number of mining equipment and heat pumps and the costs of individual components ($\mathrm{AC}^\mathrm{Miner}$ and AC^HP), which are summed to obtain the total initial expenditure (CAPEX).

$$\mathrm{CAPEX} = C^\mathrm{Miner} + C^\mathrm{HP} \tag{12}$$

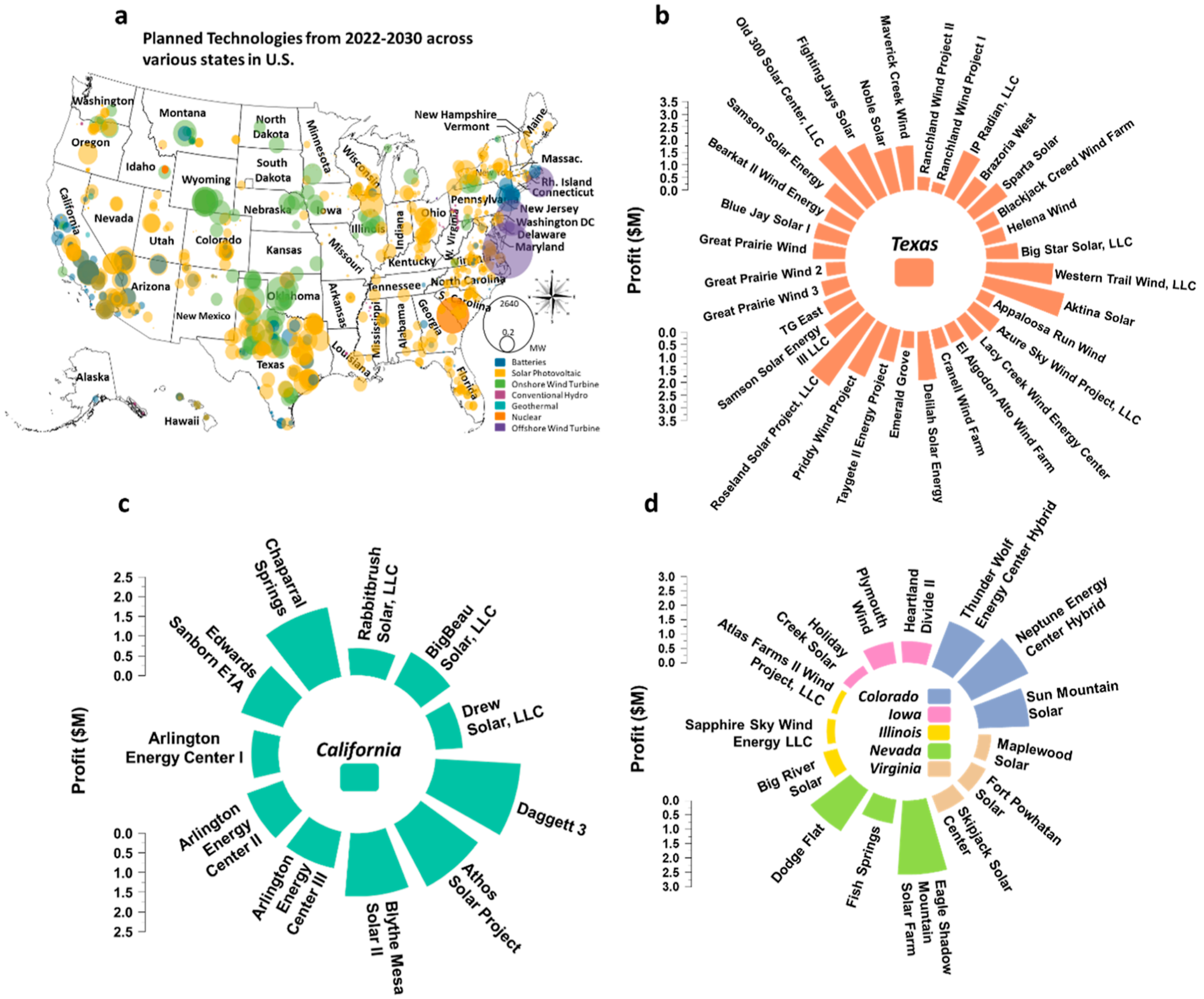

Figure 2. (a) Planned technologies from 2022 to 2030 across various states in the U.S. (b) Profitability of planned solar and wind installations in Texas based on bitcoin mining. (c) Profitability of planned solar installations in California based on using bitcoin mining. (d) Profitability of planned solar and wind installations in Colorado, Iowa, Illinois, Nevada, and Virginia based on using bitcoin mining.

$$C^{\text{Miner}} = N^{\text{Miner}} \cdot AC^{\text{Miner}} \tag{13}$$

$$C^{\text{HP}} = N^{\text{HP}} \cdot AC^{\text{HP}} \tag{14}$$

When the precommercial phase concludes, the planned installation operators can recoup some initial investment in the bitcoin mining setup. As an illustration, a few alternatives are available in the market, allowing planned installation operators to sell the used mining equipment.[46,47] In the case of heat pumps, a previous study indicates a steady increase in heat pump deployment over the next decade.[48] This growing market trend suggests that planned installation operators can successfully salvage their auxiliary heat pump setup at the end of the precommercial phase, which is considerably shorter than the total operating life of heat pumps.[49] Now, based on the considered project life and the components used, the total salvage value (SAL) can be calculated using eqs 15−17.

$$\text{SAL}^{\text{Miner}} = \text{sMiner} \cdot C^{\text{Miner}} \tag{15}$$

$$\text{SAL}^{\text{HP}} = \text{sHP} \cdot C^{\text{HP}} \tag{16}$$

$$\text{SAL} = \text{SAL}^{\text{Miner}} + \text{SAL}^{\text{HP}} \tag{17}$$

where $\text{SAL}^{\text{Miner}}$ and SAL^{HP} refer to the salvage values for miners and auxiliary heat pumps, respectively. Also, sMiner and sHP refer to the corresponding depreciation factors. In this study, since the miner's life is the same as the project life, zero salvage value was considered for the miners. The operating cost for the planned renewable installation (Opexrenewable) and the heat pumps (Opexhpump) can be calculated using eqs 18 and 19.

$$\text{Opexhpump} = \sum_{t \in T} P_t^{\text{HP}} \cdot \text{opfachp} \tag{18}$$

$$\text{Opexrenewable} = \sum_{t \in T} P_t^{\text{UTL}} \cdot \text{opfacrenew} \tag{19}$$

where opfachp and opfacrenew refer to the summed operational and maintenance cost units for the heat pump and renewable facility, respectively. The above optimization modeling framework was used to analyze the added profitability using bitcoin mining during the precommercial phase for all the planned renewable installations considered in the study.

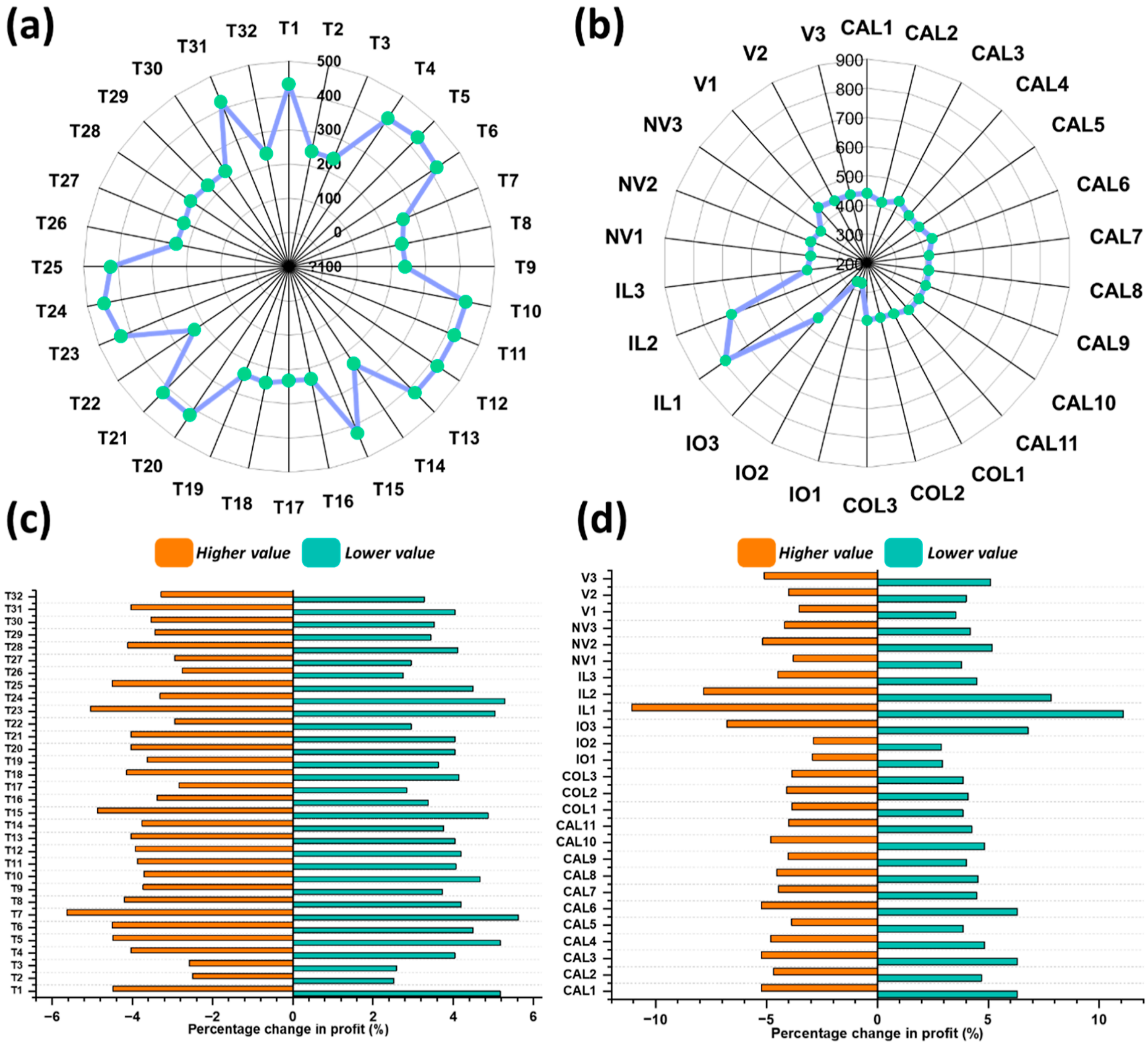

Figure 3. (a) Sensitivity analysis results based on minimum values of bitcoin mining equipment cost for the planned renewable installations in Texas. (b) Sensitivity analysis results based on minimum values of bitcoin mining equipment cost for the planned renewable installations in California, Colorado, Illinois, Iowa, Nevada, and Virginia. (c) Sensitivity analysis results based on minimum values of auxiliary equipment cost for the planned renewable installations in Texas. (d) Sensitivity analysis results based on minimum values of auxiliary equipment cost for the planned renewable installations in California, Colorado, Illinois, Iowa, Nevada, and Virginia. The abbreviations assigned to the planned renewable installations considered in this study are detailed in Table 2.

RESULTS AND DISCUSSION

As depicted in Figure 2, Texas and California emerged as states with the most planned installations that have proved profitable. Meanwhile, states such as Colorado, Illinois, Iowa, Nevada, and Virginia have fewer installations but still show profitability through bitcoin mining. Among the profitable installations, solar photovoltaics dominate, accounting for 64% of the total, with California, Colorado, Nevada, and Virginia only having solar installations that proved profitable. This trend could be due to the geographical advantage that some states have for solar or wind energy sources. In Texas, the Aktina Solar and Roseland Solar Projects, both solar photovoltaic systems with an individual nameplate capacity of 250 MW, are found to be the most profitable, generating a maximum profit of \$3.23M. However, the Western Trail Wind project, a wind energy system with a capacity of 367 MW, had a slightly lower profitability of \$2.65M. The lower profitability could be due to the distribution of available power based on the location of the facility, which can impact utilization and lead to decreased profits. It is worth noting that the profitability of a mining system hinges on various factors. Among these, the specific time intervals during which mining occurs are crucial. Specifically, the time intervals for optimal operations often coincide with periods of steady energy availability. Given the intermittent nature of renewable energy sources, the overall available power can vary significantly. This variability, in turn, affects how many bitcoins can be mined during particular time intervals. During the same interval, the market dynamics, such

Table 1. List of Notations Used in the Study

notation	description
CAPEX	total capital expenditure required to use bitcoin mining for extracting added profitability during the precommercial phase from a given planned renewable installation facility ($)
C^{HP}	total capital expenditure on the heat pumps which have been used to extract added profitability during the precommercial phase from a given planned renewable installation during the precommercial phase from a given planned renewable installation facility ($)
C^{Miner}	total capital expenditure on the mining equipment which has been used to extract added profitability during the precommercial phase from a given planned renewable installation ($)
D_t	network difficulty at different time intervals, represented by the index t (TH)
H_t	total hashing power at different time intervals corresponding to the power consumption in the mining equipment, represented by the index t (TH/s)
N^{HP}	number of heat pumps that have been used to extract added profitability from a given planned renewable installation during the precommercial phase
N^{Miner}	number of miners which have been used to extract added profitability from a given planned renewable installation during the precommercial phase
Opexhpump	total operating expenditure for the auxiliary heat pumps during the precommercial phase employing the bitcoin mining setup to extract added profitability ($)
Opexrenewable	total operating expenditure for the planned renewable installation during the precommercial phase employing the bitcoin mining setup to extract added profitability ($)
Pr	rated wind capacity for a given planned renewable installation (kW)
PROFIT	total profit from a given planned renewable installation facility using bitcoin mining during the precommercial phase ($)
Psolar_t	power output from the solar PV system in different time intervals for a given planned renewable installation, represented by the index t (kW h)
P_t^{AVAIL}	total power available from a given planned renewable installation that can be used in bitcoin mining for extracting added profitability during the precommercial phase, represented by the index t (kW h)
P_t^{heat}	total cooling load for the mining equipment in different time intervals during the precommercial phase, represented by the index t (kW h)
P_t^{HP}	total power from a given planned renewable installation used by auxiliary heat pumps during the precommercial phase, represented by the index t (kW h)
P_t^{Miner}	total power from a given planned renewable installation used by bitcoin miners during the precommercial phase, represented by the index t (kW h)
P_t^{Surplus}	total surplus power which has not been utilized from a given planned renewable installation in bitcoin mining for extracting added profitability during the precommercial phase, represented by the index t (kW h)
P_t^{UTL}	total power utilized from a given planned renewable installation in bitcoin mining for extracting added profitability during the precommercial phase, represented by the index t (kW h)
Pwind_t	power output from the wind turbine in different time intervals for a given planned renewable installation, represented by the index t (kW h)
rev_t	revenue generated from bitcoin mining in different time intervals during the precommercial phase, represented by the index t ($)
rsolar_t	incident solar radiation for a given planned renewable installation, represented by the index t (W/m^2)
SAL	total salvage value at the end of project life to use bitcoin mining for extracting added profitability during the precommercial phase from a given planned renewable installation facility ($)
$\mathrm{SAL}^{\mathrm{HP}}$	total salvage value for the heat pumps which have been used to extract added profitability during the precommercial phase from a given planned renewable installation ($)
$\mathrm{SAL}^{\mathrm{Miner}}$	total salvage value for the mining equipment which has been used to extract added profitability during the precommercial phase from a given planned renewable installation ($)
$\mathrm{SP}_t^{\mathrm{BIT}}$	bitcoin selling price at different time intervals, represented by the index t ($)
t_{m}	total mining time interval to use bitcoin mining for extracting added profitability from a given planned renewable installation facility (s)
UTL	total utilization percentage of the available power from a given planned renewable installation (%)
v_t^{s}	wind speed for a given planned renewable installation, represented by the index t (m/s)

as bitcoin selling prices and network difficulty levels, also affect the total profits. Therefore, mining profits can fluctuate based on the interplay between energy availability and market dynamics at varying times. In this regard, it is essential to size the mining farm strategically, factoring the energy fluctuations and market conditions to maximize profitability. As a result, complete utilization of the nameplate capacity may not result in increased profits. These findings indicate that bitcoin mining is an effective alternative to generate additional profits during the precommercial phase. However, in the long term, the planned installations would supply energy to the grid based on the applicability of the power purchase agreements.[50,51] Moreover, added investments would be required at the end of the precommercial phase to continue mining under profitable scenarios due to constant technological advancements in the power efficiencies of bitcoin miners.[27]

In this work, we utilize historical data on market prices and technological efficiencies, providing an empirical foundation. While this work does not model the market volatilities, we conduct a single-point sensitivity analysis to study the effect of cost parameters on the profitability that can be obtained from bitcoin mining based on power generation from planned renewable installations. It was observed that an increase in mining equipment cost did not affect the total profitability, which can be attributed to the optimal sizing of mining operations. On the other hand, a decrease in mining equipment cost led to a substantial increase in profits, as depicted in Figure 3a,b. The maximum increment in profitability was observed for the Alta Farms II Wind Project in Illinois. At the same time, the El Algodon Alto wind farm in Texas attained the minimum increment in profits based on a reduction in the mining equipment cost. Additionally, the capital expenditure on heat pumps also affected the profit, as illustrated in Figure 3c,d, but the impact was considerably less significant. At the lower range of heat pump costs, the percentage increment in profits generated among planned renewable installations varied from 2.52% to a maximum of 11.08%.

The findings indicate the potential for appropriate policy support, which could bolster the economic competitiveness of

Table 2. Serial Number Assigned to Each Planned Renewable Installation Considered in the Study, along with Their Power Source and Installed Capacity

sr. no.	state and location	power source	capacity (MW)	abbreviation
1	California——Drew Solar LLC	solar photovoltaic	50	CAL1
2	California——BigBeau Solar, LLC	solar photovoltaic	64	CAL2
3	California——Rabbitbrush Solar, LLC	solar photovoltaic	50	CAL3
4	California——Chaparral Springs	solar photovoltaic	125	CAL4
5	California——Edwards Sanborn E1A	solar photovoltaic	78	CAL5
6	California——Arlington Energy Center II	solar photovoltaic	50	CAL6
7	California——Arlington Energy Center II	solar photovoltaic	67	CAL7
8	California——Arlington Energy Center III	solar photovoltaic	66	CAL8
9	California——Blythe Mesa Solar II	solar photovoltaic	112	CAL9
10	California——Athos Solar Project	solar photovoltaic	125	CAL10
11	California——Daggett 3	solar photovoltaic	150	CAL11
12	Colorado——Sun Mountain Solar 1	solar photovoltaic	100	COL1
13	Colorado——Neptune Energy Center Hybrid	solar photovoltaic	125	COL2
14	Colorado——Thunder Wolf Energy Center Hybrid	solar photovoltaic	100	COL3
15	Iowa——Heartland Divide II	onshore wind turbine	100	IO1
16	Iowa——Plymouth Wind	onshore wind turbine	102	IO2
17	Iowa——Holliday Creek Solar	solar photovoltaic	50	IO3
18	Illinois——Alta Farms II Wind Project, LLC	onshore wind turbine	101	IL1
19	Illinois——Sapphire Sky Wind Energy LLC	onshore wind turbine	130	IL2
20	Illinois——Big River Solar	solar photovoltaic	75	IL3
21	Nevada——Dodge Flat	solar photovoltaic	100	NV1
22	Nevada——Fish Springs	solar photovoltaic	50	NV2
23	Nevada——Eagle Shadow Mountain Solar Farm	solar photovoltaic	150	NV3
24	Texas——Big Star Solar, LLC (Hybrid)	solar photovoltaic	100	T1
25	Texas——Helena Wind	onshore wind turbine	125	T2
26	Texas——Blackjack Creek Wind Farm	onshore wind turbine	120	T3
27	Texas——Sparta Solar	solar photovoltaic	125	T4
28	Texas——Brazoria West	solar photovoltaic	100	T5
29	Texas——IP Radian, LLC	solar photovoltaic	150	T6
30	Texas——Ranchland Wind Project I	onshore wind turbine	58	T7
31	Texas——Ranchland Wind Project II	onshore wind turbine	74	T8
32	Texas——Maverick Creek Wind	onshore wind turbine	246	T9
33	Texas——Noble Solar	solar photovoltaic	138	T10
34	Texas——Fighting Jays Solar Project	solar photovoltaic	175	T11
35	Texas——Old 300 Solar Center, LLC	solar photovoltaic	215	T12
36	Texas——Samson Solar Energy	solar photovoltaic	125	T13
37	Texas——Bearkat II Wind Energy LLC	onshore wind turbine	163	T14
38	Texas——Blue Jay Solar I, LLC	solar photovoltaic	105	T15
39	Texas——Great Prairie Wind	onshore wind turbine	179	T16
40	Texas——Great Prairie Wind 2	onshore wind turbine	105	T17
41	Texas——Great Prairie Wind 3	onshore wind turbine	150	T18
42	Texas——TG East	onshore wind turbine	168	T19
43	Texas——Samson Solar Energy III LLC	solar photovoltaic	125	T20
44	Texas——Roseland Solar Project, LLC	solar photovoltaic	250	T21
45	Texas——Priddy Wind Project	onshore wind turbine	303	T22
46	Texas——Taygete II Energy Project	solar photovoltaic	102	T23
47	Texas——Emerald Grove	solar photovoltaic	54	T24
48	Texas——Delilah Solar Energy LLC	solar photovoltaic	150	T25
49	Texas——Cranell Wind Farm LLC	onshore wind turbine	110	T26
50	Texas——El Algodon Alto Wind Farm, LLC	onshore wind turbine	101	T27
51	Texas——Lacy Creek Wind Energy Center	onshore wind turbine	151	T28
52	Texas——Azure Sky Wind Project, LLC Hybrid	onshore wind turbine	176	T29
53	Texas——Appaloosa Run Wind	onshore wind turbine	86	T30
54	Texas——Aktina Solar	solar photovoltaic	250	T31
55	Texas——Western Trail Wind, LLC	onshore wind turbine	367	T32
56	Virginia——Skipjack Solar Center	solar photovoltaic	88	V1
57	Virginia——Fort Powhatan Solar	solar photovoltaic	75	V2
58	Virginia——Maplewood Solar	solar photovoltaic	60	V3

planned renewable installations through bitcoin mining. Our initial policy recommendation is to explore the potential for flexible approaches to decarbonization that incorporate unconventional and innovative applications such as cryptocurrency mining. Crypto operations such as bitcoin mining offer economically favorable opportunities for numerous planned renewable installations spread across different counties. This systematic approach highlights the potential of blockchain applications like bitcoin to have a positive impact on energy system operations and sustainability by serving as a shock absorber in the volatile energy market.[52] Along similar lines, bitcoin mining could be the means to use surplus renewable power generation and reduce yearly curtailments.[53] Therefore, policymakers and funding agencies should en-

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Table 3. Parameters Used in the Optimization Modeling Framework

parameters	value	unit
$\mathrm{AC}^{\mathrm{HP}}$[35]	300,000	$/unit
$\mathrm{AC}^{\mathrm{Miner}}$[61]	3395	$/unit
COP[24]	1.5	
hf[32]	0.38	
opfachp[62]	0.00207	$/kW h
opfacsolar[63]	22.64	$/kW year
opfacwind[63]	43	$/kW year
$P_{\mathrm{MAX}}^{\mathrm{HP}}$[32]	1000	kW h
$P_{\mathrm{MIN}}^{\mathrm{HP}}$[32]	0	kW h
$P_{\mathrm{MAX}}^{\mathrm{Miner}}$[33]	3.25	kW h
$P_{\mathrm{MIN}}^{\mathrm{Miner}}$[33]	0	kW h
R[36]	6.25	
sHP[64]	0.242	
sMiner[64]	0	
v_{cin}[38]	2	m/s
v_{cout}[38]	25	m/s
v_{r}[38]	11	m/s
μ^{PV}[37]	0.25	

courage future investments in renewable power generation, as well as explore the potential for added profitability during the precommercial operation of planned installations. Accordingly, by adopting measures to promote domestic energy production, we can reduce the potential risks of price volatility and supply disruption in the global energy market. Moreover, the added economic benefits generated by crypto operations can help attract private investment into the renewable energy sector, providing a much-needed boost to the development of renewable energy infrastructure. As a result, the overall costs of renewable energy systems can be reduced, increasing their accessibility to the general public.

The bitcoin industry predominantly operates on grid-powered miners in the current practice, hence, associated with a staggering carbon footprint. Correspondingly, the impact of cryptoassets on energy policies is a growing concern, with the demand for bitcoin driving energy-intensive mining operations. Some states, like New York, have passed legislation to ban cryptocurrency mining operations that utilize fossil-based energy sources.[54] While legislative actions like these hamper the growth of fossil-heavy crypto operations, it is equally essential to make cleaner mining operations cost-effective. Instead of limiting the growth of the industry, it is more practical to use clean energy sources for bitcoin mining. Accordingly, our second policy recommendation is incentivizing crypto operations based on cleaner energy sources through carbon credits. These carbon credits could be issued for the avoided emissions based on crypto operations using planned renewable installations. As an illustration, the Biden administration implemented a US $85 credit for each metric ton of carbon dioxide captured and stored to widen the use of negative emission technologies.[55] Likewise, incremental income generated through crypto operations facilitated by carbon credits during the period prior to grid integration of renewable infrastructure could serve as an effective risk reduction mechanism. Additionally, the allocation of carbon credits can also drive investment into research and development aimed at reducing the energy consumption of crypto operations, leading to further innovations in the field. As a result, integrating bitcoin mining with planned renewable installations can attain combined positive effects on climate change mitigation, improved renewable power capacity, and additional profits during precommercial operation.

Our final recommendation is to enhance location-specific renewable energy penetration through crypto operations. From a policy standpoint, it is important to realize that the intrinsic value of any cryptocurrency operation rests in its actual monetary worth. The findings of this study show that we can generate additional profits before any renewable installation supplies power to the grid. Subsequently, the generated profits should be pumped back into renewable infrastructure development. This strategy would ultimately lead to a “virtuous cycle” for incrementing renewable infrastructure. The positive feedback loop could lead to renewable infrastructure development in locations different from its origin. Similarly, the type of facility developed for renewable installations could also vary from the original plan if the crypto industry experiences another “bull run”. In the case of a dramatic surge in bitcoin prices, some installations can be exclusively allocated for crypto mining, generating the monetary support required to expedite the development of other planned installations at different locations. This approach of using the profits generated from crypto operations to fund renewable energy development could be an effective way to have a positive impact on the renewable energy transition of the country and reduce the dependence on fossil fuels.[56] Moreover, we can generate green jobs in the renewable energy sector and contribute to the growth of the local economy. To ensure the success of the proposed approach, it is essential to have supportive policies in place that incentivize the growth of renewable energy and its integration with crypto operations.

Although the findings of this study indicate that bitcoin mining presents innovative opportunities in utilizing surplus renewable energy from planned renewable installations and facilitating energy transition, it is also imperative to acknowledge the broader concerns associated with it. Bitcoin mining continues to be highly energy-intensive due to the adopted consensus algorithm.[57] The annual energy consumption of bitcoin mining stands at 115 TW h, equivalent to the power consumption of The Netherlands.[58] Based on this energy consumption, previous studies have pointed out the significant climate impact stemming from bitcoin due to the power supply from nonrenewable sources.[27,28] Moreover, accurate data on the percentage of bitcoin mining that is off the fossil-dependent power grids are challenging to obtain, as the industry is constantly evolving, and mining operations can be secretive or transient. Apart from the climate impact of bitcoin mining, it can affect several other environmental impact indicators, such as metal depletion.[59] Accordingly, it becomes crucial to consider the impact of bitcoin on the environment beyond energy use. For example, bitcoin is always associated with an e-waste problem. In the current state of mining hardware, they become obsolete after roughly every 2 years due to continuous advancements in the energy efficiency of miners and have no use beyond bitcoin mining. The annualized e-waste generated from bitcoin mining could amount to 10,948 t.[60]

■ CONCLUSIONS

The transition toward renewable energy has emerged as a global priority but is often hindered by challenges, such as the lack of efficient energy storage solutions and the economic risks faced by investors. A major obstacle for new renewable

Table 4. Prominent Output Variables, Including Profit ($M), Number of Miners ($N^{\mathrm{Miner}}$), Number of Heat Pumps (N^{HP}), and Utilization Percentage (UTL) for the Different Planned Renewable Installations Using Bitcoin Mining to Gain Added Profits during Precommercial Operation

sr. no.	profit ($M)	N^{Miner}	N^{HP}	UTL
1	0.69	974.00	2.00	0.32
2	0.93	1176.00	2.00	0.30
3	0.69	974.00	2.00	0.32
4	1.81	2352.00	4.00	0.31
5	1.13	1176.00	2.00	0.25
6	0.69	974.00	2.00	0.32
7	0.97	1176.00	2.00	0.29
8	0.96	1176.00	2.00	0.30
9	1.62	1764.00	3.00	0.26
10	1.81	2352.00	4.00	0.31
11	2.17	2352.00	4.00	0.26
12	1.69	1764.00	3.00	0.29
13	2.13	2352.00	4.00	0.31
14	1.69	1764.00	3.00	0.29
15	0.74	588.00	1.00	0.26
16	0.76	588.00	1.00	0.26
17	0.32	440.00	1.00	0.24
18	0.20	459.00	1.00	0.22
19	0.28	588.00	1.00	0.22
20	0.49	588.00	1.00	0.22
21	1.72	1764.00	3.00	0.28
22	0.84	1068.00	2.00	0.33
23	2.60	2940.00	5.00	0.31
24	1.26	1629.00	3.00	0.27
25	0.87	588.00	1.00	0.29
26	0.84	588.00	1.00	0.30
27	1.62	1764.00	3.00	0.24
28	1.26	1629.00	3.00	0.27
29	1.94	2352.00	4.00	0.27
30	0.39	395.00	1.00	0.40
31	0.52	504.00	1.00	0.40
32	1.75	1677.00	3.00	0.40
33	1.76	1764.00	3.00	0.22
34	2.25	2352.00	4.00	0.23
35	2.77	2940.00	5.00	0.23
36	1.62	1764.00	3.00	0.24
37	1.16	1111.00	2.00	0.40
38	1.34	1710.00	3.00	0.27
39	1.29	1176.00	2.00	0.39
40	0.77	588.00	1.00	0.34
41	1.05	1022.00	2.00	0.40
42	1.20	1145.00	2.00	0.40
43	1.62	1764.00	3.00	0.24
44	3.23	3528.00	6.00	0.24
45	2.22	1764.00	3.00	0.35
46	1.30	1661.00	3.00	0.27
47	0.66	588.00	1.00	0.19
48	1.94	2352.00	4.00	0.27
49	0.79	588.00	1.00	0.33
50	0.74	588.00	1.00	0.35
51	1.06	1029.00	2.00	0.40
52	1.26	1176.00	2.00	0.40
53	0.62	586.00	1.00	0.40
54	3.23	3528.00	6.00	0.24
55	2.65	2352.00	4.00	0.38
56	0.62	588.00	1.00	0.17
57	0.54	588.00	1.00	0.20
58	0.43	558.00	1.00	0.23

projects was the underutilization of assets until they supplied power to the grid. Correspondingly, with the escalating climate concerns associated with the ongoing state of bitcoin mining operations, it was crucial to investigate ways to use this popular demand for bitcoin as an aid toward a sustainable and climate-friendly future. Thus, in this work, we investigated the potential of bitcoin to support the planned renewable installations in the U.S. using added profitability during the precommercial phase. With the help of this novel contribution, we could leverage the demand for bitcoin to benefit the energy transition rather than aggravating the existing challenges. The findings indicated that bitcoin mining, an activity often criticized due to its energy-intensive nature, could serve as a bridge to foster investments in renewable energy. Bitcoin mining proved profitable in all of the examined planned installations, and by adopting this approach, investors could generate economic returns from otherwise unutilized assets. Simultaneously, this strategy could address the climate impact of conventional bitcoin mining operations, which rely on fossil-dominant grids. Therefore, integrating bitcoin mining with planned renewable installations could enhance the economic potential of renewable projects during their precommercial operation phase and correspondingly mitigate the climate challenges tied to traditional mining practices. Thus, this work emphasizes bitcoin mining as a compelling alternative for policymakers and investors with regard to power utilization from planned renewable installations.

■ APPENDIX

Tables 1−4 depict the additional information used in the study, including the list of notations, characteristics for the planned renewable installations, parameters used in the optimization modeling framework, and prominent output variables obtained for each planned installation.

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Notes

The authors declare no competing financial interest.

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