Policy assessments for the carbon emission flows and sustainability of Bitcoin blockchain operation in China

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Abstract

The large energy consumption and the associated carbon emission of the Bitcoin blockchain operations are growing to a non-negligible problem that could potentially undermine the sustainable efforts of many countries around the world. In this paper, we make the first and original attempt to investigate the carbon emission flows of the Bitcoin blockchain operations in China under different carbon policies with a Bitcoin blockchain carbon emission (BBCE) model. We find that without any policy interventions, the annual energy consumption of the Bitcoin blockchain in China is expected to maximize in 2024 at 296.59 Twh and generate 130.50 million metric tons of carbon emission flows correspondingly, which would exceed the annualized greenhouse gas emission level of the Czech Republic and Portugal in 2016. Moreover, the maximum carbon emission per GDP of the Bitcoin industry is estimated to reach 10.77 kg/USD in June 2026 based on benchmark assessments. In addition, policies that induce changes in the energy consumption structure of the mining activities may be more effective than intuitive punitive measures in limiting the total amount of carbon emission in the Bitcoin blockchain operation. In particular, we find that market access policy has an incentive effect on the emission reduction of the Bitcoin industry. After evaluating the policy effectiveness, we provide some novel insights for the sustainable operations of the disruptive blockchain technology by analyzing the carbon emissions pattern of the Bitcoin blockchain.

Keywords: Blockchain; Bitcoin; Sustainability; Carbon emission; Policy design

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As Bitcoin attracted a considerable amount of attention in recent years, its underlying core mechanism, namely blockchain technology, has also quickly gained popularity. Due to its key characteristics such as decentralization, auditability and anonymity, blockchain is widely regarded as one of the most promising and attractive technologies for a variety of industries, such as supply chain finance, production operations management, logistics management and the Internet of Things (IoT) [1,2,3]. Although blockchain is widely regarded as one of the most promising and attractive technologies for a variety of industries, its first application in the actual operation of the Bitcoin network indicates that there exist a non-negligible energy and carbon emission drawback with the current consensus algorithm. Therefore, there is an urgent need to address this issue. This paper take the first and original attempt to take the initial steps by quantifying the current and future carbon emission patterns of Bitcoin blockchain operations in China under different carbon policies. In recent years, the system dynamics (SD) based model is widely introduced for carbon emission flows estimation for a specific area or industry[4,5]. In comparison to its counterparts, SD modelling has the two main advantages in carbon emission flows assessment: firstly, with the help of the feedback loops of stock and flow parameters combined, system dynamics technique is able to capture the interactions of variables in a complex system, which enables the simulation and estimation of specific industry operations[6,7,8]. In addition, intended policies can be adjusted for scenario policy effectiveness evaluation, since the SD based model is focused on disequilibrium dynamics of the complex system[9,10]. Based on system dynamics modeling, we develop the Bitcoin blockchain carbon emission model (BBCE) to assess the carbon emission flows of the Bitcoin network operations in China under different scenarios.

This paper serves as the original attempt to use the theory of carbon footprint to create the theoretical model for Bitcoin blockchain carbon emission assessment and policy evaluation [11,12]. First, we establish the system boundary and feedback loops for the Bitcoin blockchain carbon emission system, which serve as the theoretical framework to investigate the carbon emission mechanism of the Bitcoin blockchain. The BBCE model consists of three interacting subsystems: Bitcoin blockchain mining and transaction subsystem, Bitcoin blockchain energy consumption subsystem and Bitcoin blockchain carbon emission subsystem. Specifically speaking, transactions packaged in the block are confirmed when the block is formally broadcasted to the Bitcoin blockchain. To increase the probability of mining a new block and getting rewarded, the mining hardware will be updated continuously and invested by network participants for a higher hash rate, which would cause the hash rate of the whole network to rise. The network mining power in is determined by two factors: first, the network hash rate (hashes computed per second) positively accounts for the mining power increase in the Bitcoin blockchain when high hash rate miners are invested; second, the power usage effectiveness (PUE) is introduced to illustrate the energy consumption efficiency of Bitcoin blockchain as suggested by Stoll[13]. Finally, the network energy cost of the Bitcoin mining process is determined by the network energy consumption and average electricity price, which further influences the dynamics behaviors of Bitcoin miner's investment. Then, the BBCE model collects the carbon footprint of Bitcoin miners both in heavy and clean energy regions and formulates the overall carbon emission flows of the whole Bitcoin blockchain in China. The level variable GDP consists of Bitcoin miner's income and total cost, which reflects the productivity of the Bitcoin blockchain. It also serves as an auxiliary factor to generate the carbon emission per GDP in our model, which provides guidance for policy makers in implementing the punitive carbon taxation on the Bitcoin industry. Bitcoin blockchain reward halving occurs every four years, which means that the reward of broadcasting a new block in Bitcoin blockchain will be zero in 2140. As a result, the Bitcoin market price increases periodically due to the halving mechanism of Bitcoin blockchain. Finally, by combining both carbon cost and energy cost, the total cost of the Bitcoin mining process provides negative feedback for miner's income and their investment strategies. Miners will gradually stop investing and updating mining hardware in China when the total cost exceeds the income in our BBCE simulation. The whole theoretical relationships of BBCE parameters are demonstrated in Figure 5.

We find that the annualized energy consumption of the Bitcoin blockchain in China will reach its maximum in 2024 at 296.59 Twh based on the benchmark simulation, which exceeds the electricity consumption level of Italy and Netherland and ranks 13th among all countries in 2016.

Correspondingly, the carbon emission flows of the Bitcoin operations are expected to maximize at 130.50 million metric tons per year in 2024, which surpasses the total greenhouse gas emission level of the Czech Republic and Portugal in 2016 peported by cia.gov under the benchmark scenario without any policy intervention. In addition, the maximized carbon emission per GDP of the Bitcoin industry is estimated to reach 10.77 kg/USD based on system dynamics assessments. The BBCE simulation results suggest that some commonly implemented carbon emission policies, such as carbon taxation, are relatively ineffective for the Bitcoin industry. On the contrary, site regulation policies for Bitcoin miners are able to provide effective negative feedbacks for the carbon emission of Bitcoin blockchain operations.

Compared with the previous studies, the main contributions of this paper are as follows: First, to the best of our knowledge, none of the existing literature establishes a systematic theoretical framework to assess the carbon emission flows and productivity of the Bitcoin industry in China, which are unaccounted for in the current GDP and carbon emissions calculations. Second, this paper firstly evaluates and assess multiple feasible policies for Bitcoin carbon emissions regulation through a system dynamics model, which indicates that some common policies used for common emissions control are not effective due to the unique characteristics of the PoW algorithms in the Bitcoin blockchain. Third, some novel insights are provided for the sustainable operations of the disruptive blockchain technology by analyzing the carbon emissions pattern of the Bitcoin blockchain.

The energy and carbon emission problem of PoW algorithm in China

Although the PoW has enabled Bitcoin blockchain to operate in a relatively stable manner, several unexpected behaviors of the Bitcoin blockchain have been detected: first, the attractive financial incentive of Bitcoin mining has caused an arms race in dedicated mining hardware[14]. The mining hardware has evolved through several generations. Initially, miners used the basic Central Processing Unit (CPU) on general-purpose computers. Then, a shift was made to the Graphic Processing Unit (GPU) that offered more power and higher hash rates than the CPU. Finally, the Application-Specific Integrated Circuits (ASICs) that were optimized to perform hashing calculations were introduced. Nevertheless, the rapid hardware development and fierce competition have significantly increased the capital expenditure for Bitcoin mining[15]; second, the Bitcoin mining activity and the constant-running mining hardware has led to large energy consumption volume. Previous literature has estimated that the Bitcoin blockchain could consume as much energy per year as small to medium-sized countries such as Denmark, Ireland, or Bangladesh[16]; finally, the large energy consumption of the Bitcoin blockchain has created considerable carbon emissions. It is estimated that between the period of January 1st, 2016 and June 30th, 2018, up to 13 million metric tons of CO_2 emissions can be attributed to the Bitcoin blockchain[17]. Although the estimate ranges vary considerably, they have indicated that energy consumption of network and its corresponding environmental impacts have become a non-negligible issue.

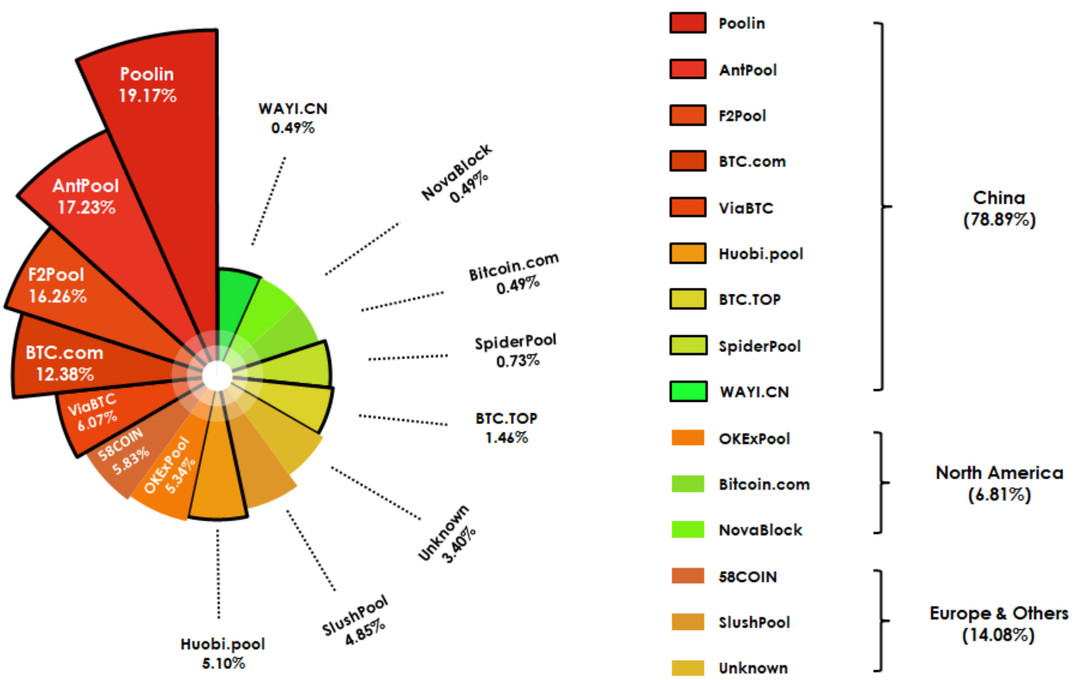

Fig. 1 | Mining pool distributions of Bitcoin blockchain. As of April 2020, China accounts for more than 75% of Bitcoin blockchain operation around the world. Some rural areas in China are considered as the ideal destination for Bitcoin mining, which is mainly due to the cheaper electricity price and large undeveloped land for pool construction. The mining pool statistics is obtained from https://btc.com/stats.

The growing energy consumption and the environmental impacts of the Bitcoin blockchain have posed problems for many countries, especially for China. Due to the closeness to manufacturers of specialized hardware and access to cheap electricity, a majority of the mining process has been conducted in China as miners in the country account for more than 75% of the Bitcoin network's hashing power, as shown in Figure 1. As one of the largest energy consuming countries on the planet, China is a key member of greenhouse gas reduction ratifications in the Paris Agreement[18,19,20]. However, without appropriate interventions and feasible policies, the intensive Bitcoin blockchain operations in China can quickly grow as a threat that could potentially undermine the emission reduction effort taken place in the country [10].

Table 1 | Scenario parameter settings

Scenarios	Measures	Market access	Miner site selection	Carbon tax
Benchmark (BM)	Baseline policy intervention	100%	40%	2
Market access (MA)	Raise the market access standards for Bitcoin miners	50%	40%	2
Site regulation (SR)	Strict regulation on Bitcoin industry in the coal-heavy area	100%	20%	2
Carbon tax (CT)	Extra Punitive carbon tax on Bitcoin mining	100%	40%	5

Note: Exogenous auxiliary parameters are introduced to assess the carbon emission flows under different Bitcoin policy measures. In terms of variable settings, three main parameters are chosen as the scenario factors in the proposed BBCE model, including market access (MA), miner site regulation (SR) and carbon tax (CT).

Suggested by the previous work[21] and the subsystems of our proposed BBCE model, we consider three main Bitcoin policies conducted at a different stage of the Bitcoin mining industry, which then formulates the four scenario assessments for Bitcoin blockchain carbon emission flows (in Table 1). In detail, Benchmark (BM) scenario is a baseline and current scenario of each policy factor, which suggests that the Bitcoin industry continues to operate under the least policy intervention. In the benchmark scenario, market access is assumed to be 100%, which indicates that profitable Bitcoin miners of all efficiencies are allowed to operate in China. Suggested by the actual regional statistics of Bitcoin miners, we assume 40% of miners are located in coal-heavy areas in the benchmark scenario. Moreover, the punitive carbon tax will be doubled if the carbon emission per GDP of the Bitcoin industry is greater than 2. In the other three scenarios, policies on different Bitcoin mining procedures are adjusted due to energy saving and emission reduction concerns. Specifically, in the Bitcoin mining and transaction subsystem, market access standard is doubled, i.e., profitable miners with low efficiency are forbidden to enter the Chinese Bitcoin market in the market access (MA) scenario, and policy makers are forced to matian the network stability of Bitcoin blockchain in a efficient manner. In the site regulation (SR) scenario, Bitcoin miners in coal-heavy areas are persuaded and suggested to relocate to the hydro-rich area, which results in only 20% of miners remaining in coal-heavy areas in the scenario. In the carbon tax (CT) scenario, a more strict carbon tax is increased to five-times the initial value to enforce more strict punishment for high carbon emission behaviors of Bitcoin blockchain. Utilizing the above scenarios, carbon emission flows and energy consumptions of Bitcoin blockchain are assessed, and the carbon and energy reduction effectiveness of different policies is evaluated in BBCE simulations from the period of 2014 to 2030.

Carbon emission flows of Bitcoin blockchain operation

The maximized annual energy consumption and carbon emission of the Bitcoin blockchain in China are expected to exceed those of some developed countries such as Italy, the Netherlands, Czech Republic and Portugal. Without any policy interventions, the carbon emission pattern of the Bitcoin blockchain will become a non-negligible barrier against the sustainability efforts of China. Figure 2 reports the annualized energy consumption and carbon emission flows of Bitcoin blockchain in China. As the baseline assessment under the least policy intervention, the benchmark scenario simulates the natural operation results of the Bitcoin blockchain. In the BM scenario, the annual energy consumption of Bitcoin blockchain in China will gradually grow and eventually maximize in 2024, at 296.59 Twh per year. In fact, electricity consumed by Bitcoin blockchain in 2024 will exceed the electricity consumption level of Italy and the Netherlands in 2016 and ranks 13 among all the countries, which indicates the energy intensive pattern of Bitcoin industry operations. Regarding the carbon tax scenario, the highest energy demand of the Bitcoin industry slightly decreases due to carbon emission penalties, at 217.37 Twh. However, the results of the market assess and site regulation scenarios indicate that the total energy consumption of the Bitcoin industry will reach 350.11 Twh and 319.80 Twh respectively in 2024 and 2025.

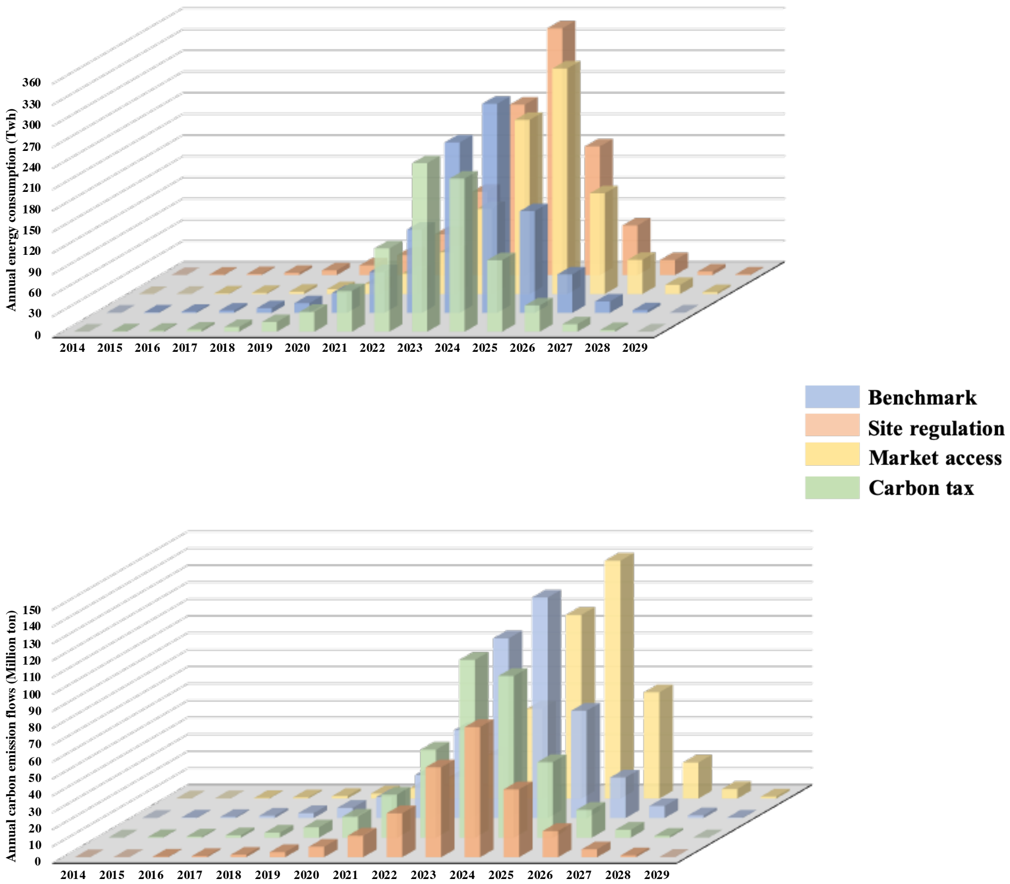

Fig. 2 | Annualized scenario simulation results. In comparison to the country-level consumption and emission statistics, annualized energy consumption (a) and carbon emission flows (b) of Bitcoin operation in China are generated through monthly simulation results of each scenario. Annual energy consumption and ranking of countries are obtained from cia.gov (www.cia.gov), carbon emission and ranking of countries are collected from global carbonatlas (www.globalcarbonatlas.org).

It is clear that the carbon emission behavior of the Bitcoin industry is consistent with the Bitcoin blockchain energy consumption intensity. As a result, in the BM scenario, annual carbon emission of the Bitcoin industry is expected to reach its maximum in 2024, at 130.50 million metric tons. In essence, the carbon emission pattern of the Bitcoin industry would become an increasing threat to China's greenhouse emission reduction target, since the estimated Bitcoin carbon emission in China exceeds the total greenhouse emission of the Czech Republic and Portugal in 2016 and ranks 36 worldwide. In comparison, the carbon emissions generated by Bitcoin blockchain significantly experienced a significant reduction in SR and CT scenarios, which illustrates the positive impact of these carbon-related policies. On the contrary, the MA scenario witnesses an extraordinary increase of Bitcoin carbon emission to 140.71 million metric tons in 2025.

Based on the scenario results of the BBCE model, the Benchmark scenario indicates that the energy consumed, and the carbon emissions generated by Bitcoin industry operations are simulated to grow continuously as long as mining Bitcoin maintains its profitability in China. This is mainly due to the positive feedback loop of the competitive mechanism of PoW, which requires advanced and high energy-consuming mining hardware for Bitcoin miners in order to increase the probability of earning block rewards. In addition, the flows and long-term trend of carbon emission simulated by the proposed system dynamics model are consistent with several previous estimations[10,13], which are devoted to precisely estimate the carbon footprint of Bitcoin blockchain.

The Paris Agreement is a worldwide agreement committed to limit the increase of global average temperature[22,23]. Under the Paris Agreement, China is devoted to cut down 60% of the carbon emission per GDP by 2030 based on that of 2005. However, according to the simulation results of the BBCE model, we find that the carbon emission pattern of Bitcoin blockchain will become a potential barrier against the emission reduction target of China, since the maximized carbon emission per GDP of Bitcoin industry is expected to sit at 10.77 kg per USD in the benchmark scenario. In addition, in the current national economy and carbon emission accounting of China, the operations of the Bitcoin blockchain have not been listed as an independent department for carbon emissions and productivity calculation. This adds difficulty for policy makers to monitor the actual behaviors of the Bitcoin industry and design well-directed policies. In fact, the energy consumption per transaction of Bitcoin netwok is larger than lots of mainstream financial transactions channels[17]. To address this issue, we suggest policy makers to set up separated accounts for the Bitcoin industry in order to better manage and control its carbon emission behaviors in China.

Carbon policy effectiveness evaluation

Policies that induce changes in the energy consumption structure of the mining activities may be more effective than intuitive punitive measures in limiting the total amount of energy consumption and carbon emission in the Bitcoin blockchain operation. Figure 3 presents the values of key parameters simulated by BBCE model. The carbon emission per GDP of the BM scenario in China is larger than that of all other scenarios throughout the whole simulation period, reaching a maximum of 10.77kg per USD in June 2026. However, we find that the policy effectiveness under the MA and CT scenario is rather limited on carbon emission intensity reduction, i.e., the policy effect of market access is examined to reduce in August 2027 and the carbon tax is expected to be effective until July 2024. Among all the intended policies, the SR scenario is simulated to significantly cut the carbon emission per GDP of the Bitcoin industry to 6 kg per USD in its maximum. Overall, the carbon emissions per GDP of the Bitcoin industry far exceed the average industrial carbon intensity of China, which indicates that Bitcoin blockchain operation is a highly carbon intense industry.

In the BM scenario, Bitcoin miner profits are expected to drop to zero in April 2024, which suggests that the Bitcoin miners will gradually stop mining in China and relocate their operations elsewhere. Correspondingly, the network hash rate is computed to reach 1775 EH per second in the BM scenario and the miner total cost will maximize to 1268 million dollars. Comparing the scenario results for the three policies, the profitability of mining Bitcoin in China is expected to deteriorate more quickly in the CT scenario. On the other hand, Bitcoin blockchain can maintain profitability for a longer period in MA and SR scenarios.

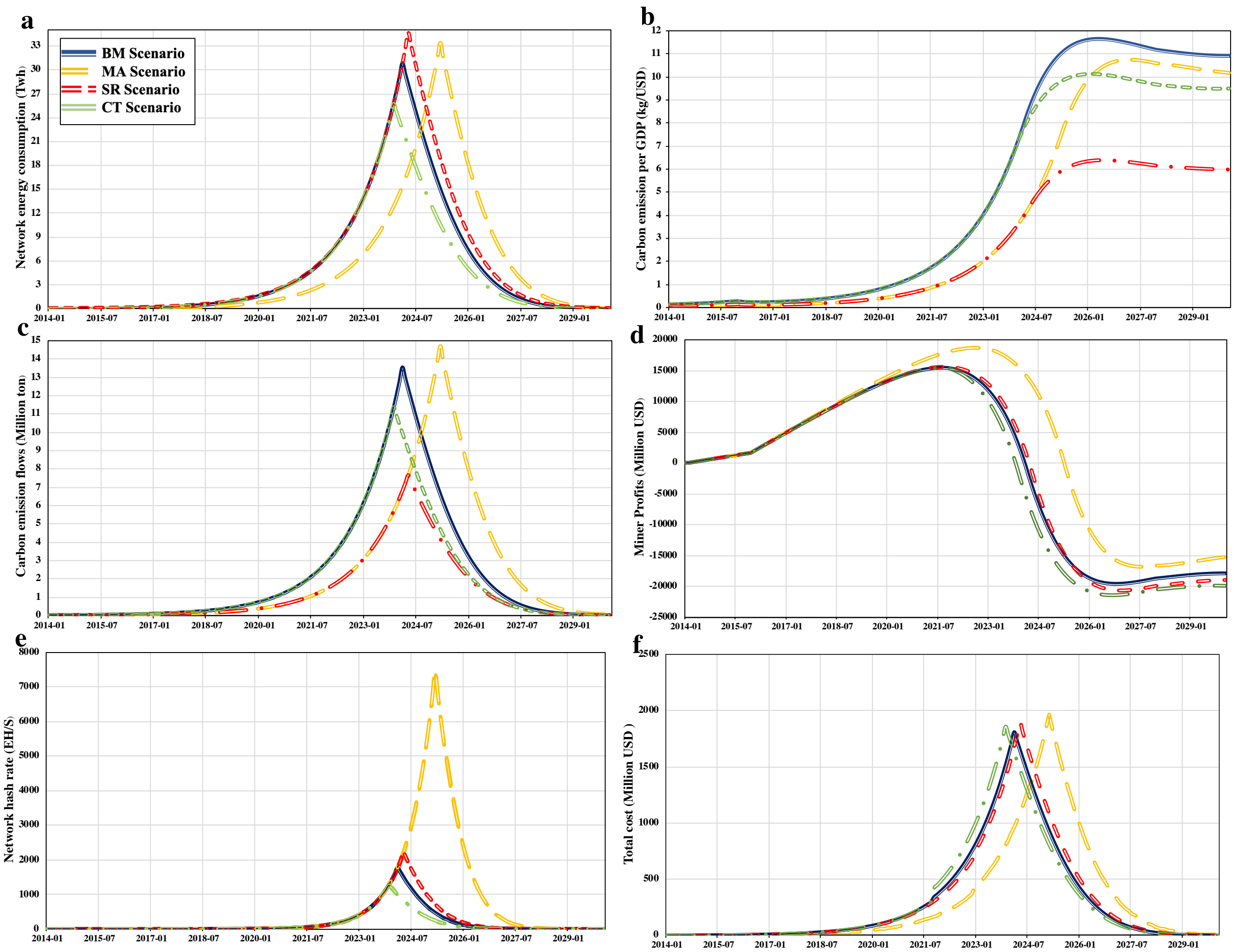

Fig. 3 | BBCE scenario assessment comparisons. a-f, monthly energy consumption (a), carbon emission flow (b), carbon emission per GDP (c), miner profits (d), network hash rate (e) and miner total cost (f) under each intended policy are simulated and calculated by BBCE framework. Based on the regressed parameters of the BBCE model, the whole sample timesteps of network carbon emission assessment cover the period from January 2014 to January 2030.

Some attracting conclusions can be drawn based on the results of BBCE simulation: Although the MA scenario enhances the market access standard to increase Bitcoin miners' efficiencies, it is regarded as an emission-prompted policy rather than an emission-reduced policy based on the simulation results. In the MA scenario, we observe the phenomenon of "Incentive Effects" proposed by previous works, which is identified in other fields of industrial policies, such as monetary policies, transportation regulations and firm investment strategies[24,25,26]. In essence, the purpose of the market access policy is to limit the mining operations of low-efficiency Bitcoin miners in China. However, the survived miners are all devoted to squeezing more proportion of the network hash rate, which enables them to stay profitable for a longer period. In addition, the Bitcoin industry in China is simulated to generate more CO_2 emissions under the MA scenario, which is mainly due to the Proof-of-Work (PoW) algorithm and profit-pursuit behaviors of Bitcoin miners. The results of the MA scenario indicate that market-related policy is likely to be less effective in dealing with high carbon emission behaviors of the Bitcoin blockchain operations.

The carbon taxation policy is widely acknowledged as the most effective and most commonly implemented policy on carbon emission reduction[27]. However, the simulation results of the CT scenario indicate that carbon tax only provides limited effectiveness for the Bitcoin industry. The carbon emission patterns of the CT scenario are consistent with the BM scenario until Bitcoin miners are aware that their mining profitabilities are affected by the punitive carbon tax on Bitcoin mining. On the contrary, the evidence from the SR scenario shows that the carbon-related policies are able to provide negative feedbacks for the carbon emissions of Bitcoin blockchain operations. In our simulation, the maximized carbon emission per GDP of the Bitcoin industry is halved in the SR scenario in comparison to that in the BM scenario.

In general, the carbon emission intensity of the Bitcoin blockchain still far exceeds the average industrial emission intensity of China under different policy interventions on the operation process of Bitcoin blockchain in China, including limiting Bitcoin mining access, altering the miner energy consumption structure and implementing carbon emissions tax. This result indicates the stable high carbon emission property of Bitcoin blockchain operations. Nevertheless, it is rather surprising to arrive at the conclusion that the newly introduced cryptocurrency based on disruptive blockchain technology is expected to become an energy and carbon-intensive industry in the near future.

Future consensus algorithm design for blockchain technology

The current Proof-of-Work consensus algorithm used in the Bitcoin blockchain can potentially undermine the wide implementation and the operational sustainability of the disruptive blockchain technology. Overall, Bitcoin is a typical and pioneering implementation of blockchain technology. Its decentralized transaction characteristics and consensus algorithm provide a novel solution for trust mechanism construction, which can be beneficial and innovative for a variety of industrial development and remote transactions. In recent years, blockchain technology has been introduced and adopted by abundant traditional industries that seek to optimize their operation process in the real world[28], such as supply chain finance[29], smart contract[30], international business and trade[31], as well as manufacturing operations[32]. In addition, a national digital currency based on blockchain technology, namely Digital Currency Electronic Payment (DCEP), is scheduled and designed by The People's Bank of China, which is expected to replace the current paper-currency based M0 supply in China.

However, the current consensus algorithm of Bitcoin, namely Proof-of-Work, gives rise to the hash rate competitions among Bitcoin miners for its potential block reward, which attracts an increasing number of miners to engage in and raise the energy consumption volumes of the whole Bitcoin blockchain. As a result, although PoW is designed to decentralized Bitcoin transactions and prevent inflation, we find that it would become an energy and carbon-intensive protocol, which eventually leads to the high carbon emission patterns of Bitcoin blockchain operation in China. The evidence of Bitcoin blockchain operations suggests that with the broaden usages and applications of blockchain technology, new protocols should be designed and scheduled in an environmentally-friendly manner. This change is necessary to ensure the sustainability of the network - after all, no one wants to witness a disruptive and promising technique to become a carbon-intensive technology that hinders the carbon emission reduction efforts around the world. The auditable and decentralized transaction properties of blockchain provide a novel solution for trust mechanism construction, which can be beneficial and innovative for a variety of industrial development and remote transactions. However, the high GHG emission behavior of Bitcoin blockchain may pose a barrier to the worldwide effort on GHG emission management in the near future. As a result, the above tradeoff is worthy of future exploration and investigation

Different from traditional industries, the carbon emission flows of “emerging” industries such as Bitcoin blockchain operation are unaccounted for in the current GDP and carbon emissions calculations. Without proper accounting and regulation, it is rather challenging to assess the carbon emission flows of these “new” industries using traditional tools such as input-output analysis. Through system dynamics modeling, our analysis effectively tackled this issue by constructing the emission feedback loops as well as capturing the carbon emission patterns. Furthermore, we are able to conduct emission assessment and evaluate the effectiveness of various potential implementable policies. Overall, our results have demonstrated that system dynamics modeling is a promising approach to investigate the carbon flow mechanisms in emerging industries.

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Methods

This paper constructs a BBCE model to investigate the feedback loops of Bitcoin blockchain and simulate the carbon emission flows of its operations in China. In view of the complexity of Bitcoin blockchain operations and carbon emission process, the system dynamics model for Bitcoin carbon emission assessment is mainly based on the following assumptions: (1) The electricity consumption of the Bitcoin mining process mainly consists of two types of energy: coal-based heavy energy and hydro-based clean energy. (2) Bitcoin price is extremely volatile in real market operations, which is inappropriate for long-term assessment in the BBCE model. Referring to the historical Bitcoin price data, we assume that the long-term Bitcoin price is mainly affected by the halving mechanism of Bitcoin mining rewards. (3) Miners stop or choose other destinations for mining if the Bitcoin mining process is no longer profitable in China. (4) Bitcoin policies are consistent with the overall carbon emission flows in China. In other words, policies such as market access of Bitcoin miners and carbon tax of the Bitcoin blockchain operations can be rejiggered for different emission intensity levels.

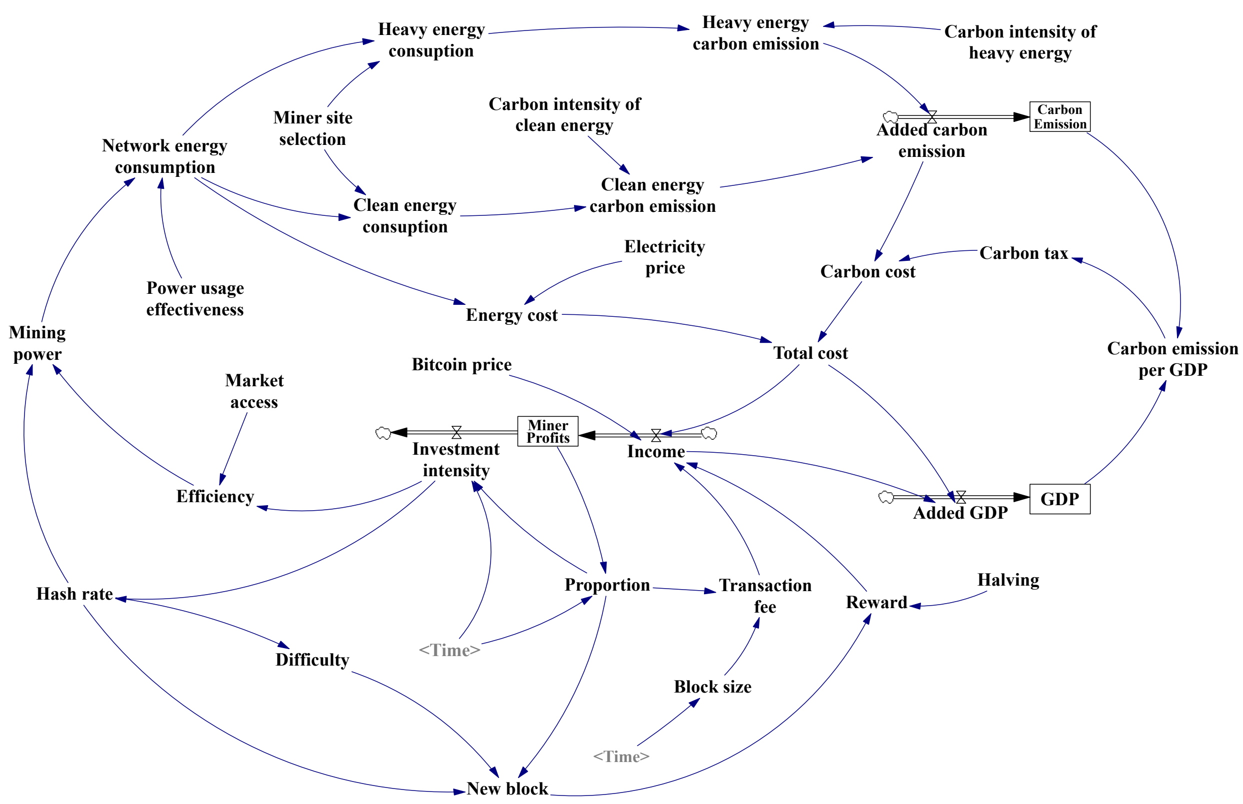

Fig. 4 | Flow diagram of BBCE modelling. Parameters of the Bitcoin blockchain carbon emission system in Figure 4 are quantified in BBCE simulations, which are suggested by the feedback loops of Bitcoin blockchain. The whole quantitative relationships of BBCE parameters are demonstrated in Appendix B.

Utilizing the flow diagram of BBCE systems illustrated in Figure 4, detailed feedback loops and flows of Bitcoin blockchain subsystems are discussed and clarified. The types, definitions, units and related references of each variable in Figure 4 are reported in Appendix A.

1) Bitcoin mining and transaction subsystem

The Bitcoin blockchain utilizes Proof-of-Work (PoW) consensus algorithm for generating new blocks and validating transactions. Bitcoin miners earn a reward if the hash value of target blocks computed by their hardware is validated by the whole network participants. On the other hand, transactions packaged in the block are confirmed when the block is formally broadcasted to the Bitcoin blockchain. To increase the probability of mining a new block and getting rewarded, the mining hardware will be updated continuously and invested by network participants for higher hash rate, which would cause the hash rate of the whole network to rise. In order to maintain the constant 10-minute per new block generation process, the difficulty of generating a new block is adjusted by the current hash rate of the whole Bitcoin network.

The halving mechanism of block reward is designed to control the total Bitcoin circulation (maximum of 21 million Bitcoins) and prevent inflation. Reward halving occurs every four years, which means that the reward of broadcasting a new block in Bitcoin blockchain will be zero in 2140. As a result, the Bitcoin market price increases periodically due to the halving mechanism of Bitcoin blockchain. With the growing popularity and broadened transaction scope of Bitcoin, the total transactions and transaction fee per block may steadily grow, which drive the other source of Bitcoin miner's income. Overall, the profit of Bitcoin mining can be calculated by subtracting the total cost of energy consumption and carbon emissions from block reward and transaction fees. Miners will stop investing and updating mining hardware in China when the total cost exceeds the income. Consequently, the whole network hash rate receives the negative feedback due to the investment intensity reductions.

2) Bitcoin energy consumption subsystem

The network mining power is determined by two factors: first, the network hash rate (hashes computed per second) positively accounts for the mining power increase in Bitcoin network when high hash rate miners are invested. However, the updated Bitcoin miners also attempt to reduce the energy consumption per hash, i.e., improve the efficiency of Bitcoin mining process, which is helpful for network mining power reduction. In addition, policy makers may raise the market access standard and create barriers for the low-efficient miners to participate in Bitcoin mining activities in China. In term of the energy consumption of the whole network, the power usage effectiveness is introduced to illustrate the energy consumption efficiency of Bitcoin blockchain as suggested by Stoll[13]. Finally, the network energy cost of Bitcoin mining process is determined by the network energy consumption and average electricity price, which further influences the dynamics behaviors of Bitcoin miner's investment.

3) Bitcoin carbon emission subsystem

The site selection strategies directly determine the energy types consumed by miners. Although the electricity cost of distinctive energies are more or less the same, their carbon emission patterns may vary significantly accordingly to their respective carbon intensity index. In comparison to miners located in hydro-rich (clean energy) regions, miners located in coal-heavy (heavy energy) regions generate more carbon emission flows under the similar mining techniques and energy usage efficiency due to the higher carbon intensity of heavy energy[17]. The proposed SD model collects the carbon footprint of Bitcoin miners both in heavy and clean energy regions, and formulates the overall carbon emission flows of the whole Bitcoin blockchain in China.

The level variable GDP consists of Bitcoin miner's income and total cost, which suggests the productivity of the Bitcoin blockchain. It also serves as an auxiliary factor to generate the carbon emission per GDP in our model, which provides guidance for policy makers in implementing the the punitive carbon taxation on Bitcoin industry. Finally, by combining both carbon cost and energy cost, the total cost of Bitcoin mining process provides a negative feedback for miner's income and their investment strategies.

The time-related Bitcoin blockchain time-series data are obtained from www.btc.com, including network hash rate, block size, transaction fee and difficulty. In addition, the auxiliary parameters and macroenvironment variables for network carbon emission flows assessment are set and considered through various guidelines. For example, the carbon intensities of different energy are suggested by Cheng et al.[32]. The average electricity cost and carbon taxation in China are collected from the World Bank. The site proportion of Bitcoin miners in China are set based on the regional statistics of Bitcoin mining pools in www.btc.com. Moreover, the monthly historical data of Bitcoin blockchain are utilized for time-related parameter regression and simulation from the period of January 2014 to January 2020. Based on the regressed parameters, the whole sample timesteps of network carbon emission assessment cover the period from January 2014 to January 2030 in this study, which is available for scenario investigations under different Bitcoin policies. The initial value of static parameters in BBCE model are shown in Table 2, and the key quantitative settings of each subsystem are respectively run as follows:

According to the guidance of the Cambridge Bitcoin Electricity Consumption Index (https://www.cbeci.org) and Küfeoğlu and Özkuran[9], Bitcoin mining equipment is required to update and invest for remaining profitability. It is clear that mining hardware in the Bitcoin network consists of various equipment and their specifications. As a result, the investment intensity in

Bitcoin blockchain is computed by the average price of a profitable mining hardware portfolio. the quantitative relationship between investment intensity and time can be expressed as the following form:

$$Investment\ intensity = \alpha_1 \times Time \times Proportion \quad (1)$$

Then the Bitcoin miner profits are accumulated by income and investment intensity flows, which can be obtained as follows:

$$Miner\ profits_t = \int_0^t (Income - Investment\ intensity)dt \quad (2)$$

As discussed above, the aim of Bitcoin mining hardware investment is to improve the miner's hash rate and the probability of broadcasting a new block. Utilizing the statistics of Bitcoin blockchain, the hash rate of the Bitcoin network is regressed, and the equation is:

$$Hash\ rate = e^{\beta_1 + \alpha_2 Investment\ intensity} \quad (3)$$

Similarly, the average block size of Bitcoin is consistent with time due to the growing popularity of Bitcoin transactions and investment. The block size is estimated by time and is illustrated as below:

$$Block\ size = e^{\beta_2 + \alpha_3 Time} \quad (4)$$

The proportion of Chinese miners in the Bitcoin mining process will gradually decrease if mining Bitcoin in China is not profitable. So, the proportion parameter in the BBCE model is set as follows:

$$Proportion = IF\ THEN\ ELSE\ (Miner\ Profits < 0, 0.7\text{-}0.01 \times Time, 0.7) \quad (5)$$

The energy consumed per hash will reduce, i.e., the mining efficiency of the Bitcoin blockchain will improve when updated Bitcoin hardware is invested and introduced. Moreover, the market access proposed by policy makers also affects network efficiency. Consequently, the network efficiency can be calculated as follows:

$$Efficiency = e^{\beta_3 + \alpha_4 \times Investment\ intensity \times Market\ access} \quad (6)$$

Then the mining power of the Bitcoin blockchain can be obtained by hash rate and efficiency. The equation of mining power is shown as follows:

$$Mining\ power = Hash\ rate \times Efficiency \quad (7)$$

Finally, the energy consumed by the whole Bitcoin blockchain can be expressed by mining power and power usage effectiveness:

$$Network\ energy\ consumption = Mining\ power \times Power\ usage\ effectiveness \quad (8)$$

Employed the regional data of Bitcoin mining pools, heavy and clean energy is proportionally consumed by distinctive Bitcoin pools. The total carbon flows in Bitcoin blockchain are measured by the sum of both monthly heavy and clean energy carbon emissions. The integration of total carbon emission is:

$$Carbon\ emission_t = \int_0^t Add\ Carbon\ emission\ dt \quad (9)$$

In addition, carbon emissions per GDP are introduced to investigate the overall carbon intensity of the Bitcoin mining process in China, which is formulated in the following equation:

$$Carbon\ emission\ per\ GDP = Carbon\ emission/GDP \quad (10)$$

In BBCE model, punitive carbon taxation on the Bitcoin blockchain will be conducted by policy makers if the carbon emission per GDP of the Bitcoin blockchain is larger than 2. As a result, the carbon tax of Bitcoin blockchain is set as:

$$Carbontax = 0.01 \times IF\ THEN\ ELSE\ (carbon\ emission\ perGDP > 2, 2, 1) \quad (11)$$

Table 2 Initial value of auxiliary parameters in the SD model

Parameter	Value	Unit	Parameter	Value	Unit
Carbon tax	0.01	USD/kg	Market access	100	%
Carbon intensity of heavy energy	0.9	Kg/kwh	Power usage effectiveness	1.1	-
Carbon intensity of clean energy	0.2	Kg/kwh	Miner site selection	40	%
Electricity price	0.05	USD/kwh	Proportion	70	%

In order to test the appropriateness of system structures and behaviors, two types model validation approaches are introduced in our study. The structural tests results indicate that the system boundary and all the system parameters are suitable for simulation, and the causal relationship between variables is appropriate. In other words, the proposed BBCE model is able to effectively reflect the causal relationship and feedback loops in Bitcoin carbon emission system. To assess the difference between real historical behaviors and system dynamics simulations, behavior validation is suggested to conduct on the key parameters in BBCE model. The behavior validation is tested by comparing the estimated parameters with their historical time-series data. In our study, key time-related variables, including hash rate and efficiency, are utilized for behavior validation. The results of behavior validation show that the of hash rate and efficiency is all greater than 0.9, at 0.977 and 0.913 respectively, which illustrate the superior behavioral suitability of the BBCE parameters. Overall, the model validation results report that the proposed BBCE model effectively simulates the nonlinear relationship of carbon emission produces in Bitcoin industry, and the parameters in BBCE model have significant consistencies with actual time-series data.

Appendix A

Table A Variable descriptions

Type	Parameter	Definition	Unit	Source
Level	Miner Profits	Total profits of Bitcoin miner in China	USD	-
	GDP	Gross productivity of Bitcoin blockchain	USD	-
	Carbon Emission	Accumulated carbon emission of Bitcoin blockchain	kg	-
Rate	Income	Bitcoin miner's income per month	USD/month	-
	Investment intensity	Investment intensity of Bitcoin miners	-	Küfeoğlu & Özkuran[9]; CBECI
	Added GDP	Gross domestic product added per month	USD/month	-
	Added carbon emission	Carbon emission of Bitcoin blockchain per month	Kg/month	-
Auxiliary	Hash rate	Hashes per second of Bitcoin network	Trillion hashes/ second	BTC.com
	Efficiency	Average mining efficiency of Bitcoin network	Joule/ Trillion hashes	Küfeoğlu & Özkuran[9]; CBECI
	Mining power	Average mining power of Bitcoin network	Watt	-
	Network energy consumption	Monthly energy consumption of Bitcoin operations	Kilowatt hour	-
	Market access	Market access standards for miners	100%	-
	Power usage effectiveness	Energy usage effectiveness of Bitcoin mining centers	-	Stoll et al.[23]
	Heavy energy consumption	Energy consumed by Bitcoin blockchain in coal-heavy region	Kilowatt hour	-
	Clean energy consumption	Energy consumed by Bitcoin blockchain in hydro-rich region	Kilowatt hour	-

Heavy energy carbon emission	Carbon dioxide generated by heavy energy miners in Bitcoin blockchain	Kg	-
Clean energy carbon emission	Carbon dioxide generated by clean energy miners in Bitcoin blockchain	Kg	-
Carbon intensity of heavy energy	Emission factor of heavy energy in China	Kg/Kilowatt hour	Cheng et al.[36]
Carbon intensity of clean energy	Emission factor of clean energy in China	Kg/Kilowatt hour	Cheng et al.[36]
Miner site selection	locations proportions of Bitcoin server in coal-heavy region	%	BTC.com
Carbon cost	Monthly carbon emission cost in Bitcoin blockchain	USD	-
Electricity price	Average electricity price in China	USD/kwh	World Bank
Energy cost	Monthly electricity cost in Bitcoin blockchain	USD	-
Total cost	Sum of carbon cost and energy cost	USD	-
Carbon tax	Average taxation for industrial carbon emission	USD/Kg	World Bank
Difficulty	Global block hash difficulty in Bitcoin blockchain	-	-
New block	New block generated by miners per month	-	-
Proportion	The proportion of Chinese miners in global Bitcoin mining system	%	BTC.com; Küfeoğlu & Özkuran[9]
Block size	Bitcoin blockchain size per month	Megabyte	BTC.com
Transaction fee	Transaction fee per month	Bitcoin	BTC.com
Bitcoin Price	Periodical Bitcoin price	USD	-
Reward	Monthly Bitcoin mined	Bitcoin	-
Halving	The Halving mechanism of Bitcoin	-	-

Appendix B

BBCE modeling equations

$Investment\ intensity$ = 40.51 × $Time$ × $Proportion$ (12)

$Proportion = IF\ THEN\ ELSE\ (Miner\ Profits < 0, 0.7\text{-}0.01 \times Time, 0.7)$ (13)

$Transaction\ fee$ = 0.115 × $Block\ size$ × $Proportion$ (14)

$Block\ size = e^{7.22+0.0215\times Time}$ (15)

$Reward = New\ block \times Halving$ (16)

$Price$=1000 + $STEP$ (5000,24) + $STEP$ (6000,72) + $STEP$ (12000,120) (17)

$Income{=}Price * (Reward + Transactionfee) - Totalcost$ (18)

$Miner\ profits\ (t) = \int_0^t (Income - Investment\ intensity)dt$ (19)

$Added\ GDP = Income + Total\ cost$ (20)

$GDP(t) = \int_0^t Added\ GDP\ dt$ (21)

$Hash\ rate = 0.7 \times e^{0.0039\times Investment\ intensity+8.16}$ (22)

$Efficiency = e^{9.3-0.0018\times Investment\ intensity \times Market\ access}$ (23)

$Mining\ power = Hash\ rate \times Efficiency$ (24)

$Network\ energy\ consumption$ = 0.7315 × $Mining\ power$ × $Power\ usage\ effectiveness$ (25)

$Energy\ cost$ = 0.05 × $Network\ energy\ consumption$ (26)

$Total\ cost = Energy\ cost + Carbon\ cost$ (27)

$Heavy\ energy\ consumption = Miner\ site\ selection \times Network\ energy\ consumption$ (28)

$Clean\ energy\ consumption = (1 - Miner\ site\ selection) \times Networkenergyconsumption$ (29)

$Heavy\ energy\ carbon\ emission = Heavy\ energy\ consumption \times$

$Carbonintensityof\mathrm{heavy}energy$ (30)

$Clean\ energy\ carbon\ emission = Clean\ energy\ consumption \times$

$Carbonintensityofcleanenergy$ (31)

$Carbon\ emission\ (t) = \int_0^t Add\ Carbon\ emission\ dt$ (32)

$Carbon\ emission\ per\ GDP = Carbon\ emission/GDP$ (33)

$Carbontax$=0.01×$IF\ THEN\ ELSE\ (carbon\ emission\ perGDP{>}2, 2, 1)$ (34)

$Added\ carbon\ emission = Heavy\ energy\ carbon\ emission + Cleanenergycarbonemission$ (35)

$Carbon\ cost = Carbon\ tax \times Added\ carbon\ emission$ (36)

Appendix C

Proof-of-Work algorithm of Bitcoin blockchain

To ensure the correctness of transactions and the stability of the system, the Bitcoin blockchain technology uses the concept of Proof-of-Work (PoW) as the current consensus algorithm. In this consensus algorithm, any new transaction that takes place in the system must be first verified and informed by a majority of miners[34]. Given that they are valid, the transactions are collected to form a block. Once a miner successfully calculates the correct hash value, the block and its corresponding hash value will be added to the blockchain, and all the local copies of the blockchain will be updated accordingly. In order to provide incentives for solving the puzzle, the consensus algorithm rewards the first miner who solved the PoW in the form of mining reward and transaction fees: on one hand, the miner receives the mining reward, which halves every 210,000 blocks, for the block it solved; on the other hand, the miner also receives the transaction fee for every successful addition of a transaction in the blockchain[35]. As a result, all the miners race to perform the PoW and calculate the correct hash value in order to collect the corresponding reward[36]. Finally, as shown in Figure 5, the large energy consumption of the Bitcoin blockchain has created considerable carbon emissions. It is estimated that between the period of January 1st, 2016 and June 30th, 2018, up to 13 million metric tons of CO_2 emissions can be attributed to the Bitcoin blockchain

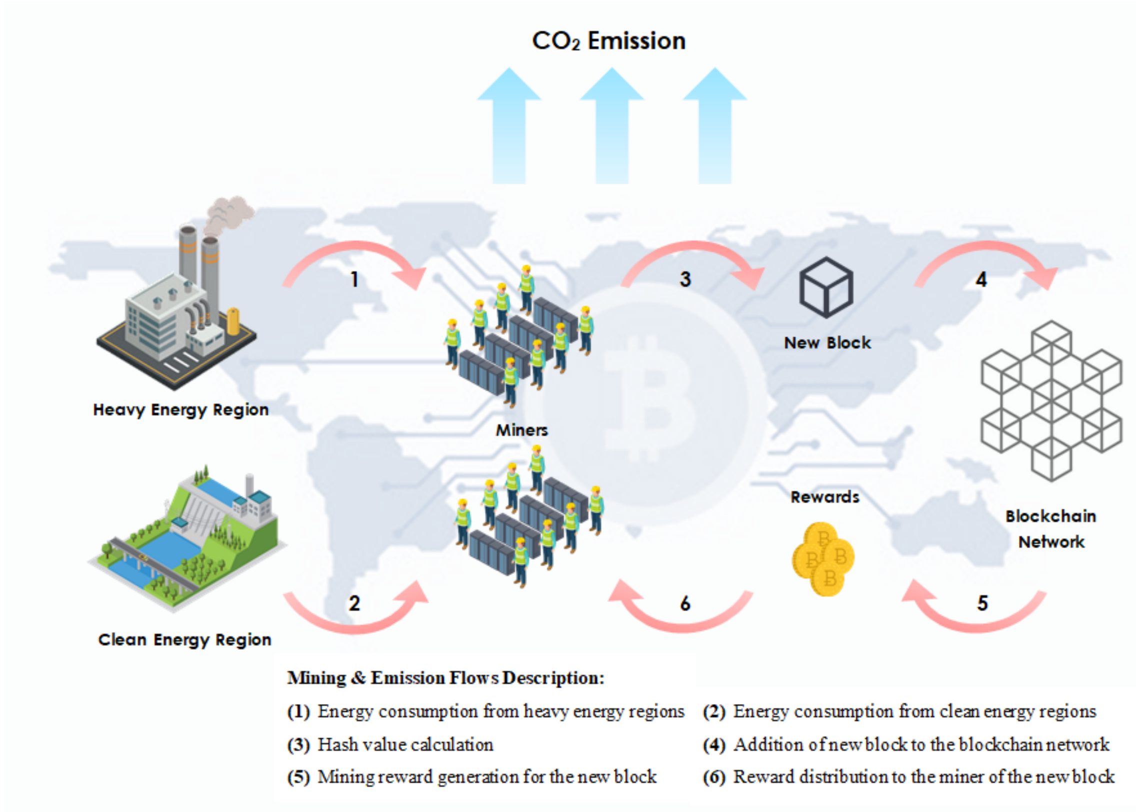

Fig. 5 | Carbon footprint for Proof-of-Work algorithm of Bitcoin blockchain. The PoW validation process of Bitcoin blockchain involves miners solving a cryptographic puzzle to adjust the nonce and generate a hash value lower than or equal to a certain target value, where miners earn 6.25 Bitcoin currently as new block reward. The mining and calculation process of Bitcoin blockchain requires steadily growing amount of energy due to the fierce competition between miners. Both heavy and clean energy consumed by Bitcoin miners are collected to formulate the carbon emission flows of the whole Bitcoin blockchain. The mining area distribution of Bitcoin blockchain is obtained from https://btc.com/stats.