Applied Energy Symposium 2021: Low carbon cities and urban energy systems
September 4-8, 2021, Matsue, Japan
Paper ID: 101

Bitcoin’s future carbon footprint

Shize Qin[1], Lena Klaaßen[2,4], Ulrich Gallersdörfer[3], Christian Stoll[4,5,*], Da Zhang[1,6,*]
1 Institute of Energy, Environment, and Economy, Tsinghua University, Beijing 100084, China
2 Climate Finance and Policy Group, Department of Humanities, Social and Political Sciences, ETH Zurich, Switzerland
3 TUM Software Engineering for Business Information Systems, Department of Informatics, Technical University of Munich, Munich, Germany
4 MIT Center for Energy and Environmental Policy Research, Massachusetts Institute of Technology, Cambridge, MA, USA
5 TUM Center for Energy Markets, TUM School of Management, Technical University of Munich, Munich, Germany
6 MIT Joint Program on the Science and Policy of Global Change, Cambridge, MA 02139, USA
*Correspondence to Christian Stoll (cstoll@mit.edu) and Da Zhang (zhangda@tsinghua.edu.cn)

ABSTRACT

The carbon footprint of Bitcoin has drawn wide attention, though Bitcoin’s long-term impact on the climate remains uncertain. In this paper, we present a framework that leverages some fundamental concepts in energy economics and finance to overcome uncertainties in previous estimates and project Bitcoin’s worldwide electricity consumption and carbon footprint in the long-term. If Bitcoin’s future market capitalization growth rate in the long-term is assumed to fall within the range of historical growth rates of several comparable mainstream financial assets, we find that the annual electricity consumption of Bitcoin may increase from 190 to 7,500 TWh between 2021 and 2100. The future carbon footprint of Bitcoin strongly depends on the decarbonization pathway of the electricity sector. If the electricity sector achieves carbon neutrality by 2060, Bitcoin’s annual carbon footprint will peak in 2023, with cumulative emissions of about 1 GtCO2 by 2100. However, in the business-as-usual scenario, emissions sum to a staggering 30 GtCO2 through 2100 — the equivalent of total global emissions from 2019. In light of these results, we discuss implications for policy in reducing Bitcoin’s future carbon footprint.

Keywords: Bitcoin; Electricity consumption; Emissions; Policy implication

NONMENCLATURE

Abbreviations	
BTC	Bitcoin
tx	*Transactions*
OTC	Over-the-counter

1. INTRODUCTION

Bitcoin, a decentralized cryptocurrency, utilizes blockchain technology to validate transactions and ensure the integrity of the network in the absence of a trusted third party (e.g., bank). The associated electricity consumption and carbon footprint of Bitcoin mining have received attention from researchers and policymakers alike in recent years.[1]-[4] Previous studies evaluated historical electricity consumption and emissions. For example, Krause et al. indicate that the electricity input to generate a $1 market value by Bitcoin mining (17 MJ) is higher than that of precious metal mining (5, 7, and 9 MJ for gold, platinum, and rare earth oxides, respectively)[1]. In total, the annual CO_2 emissions (22 megatons in 2018) match a midsize city in the U.S., such as Kansas City.[2]

Although Bitcoin becomes more salient in the global financial system, its long-term worldwide environmental impact remains uncertain. [5]-[9] Predicting the energy efficiency of future mining facilities and the future total hash rate of the mining network have turned out to be a major challenge in estimating the future electricity consumption and resulting carbon footprint of cryptocurrency mining.

In this study, we present a novel methodology that leverages some fundamental concepts in energy economics and finance to overcome uncertainties in previous studies and estimate worldwide electricity consumption and carbon footprint of Bitcoin mining in a long-time range. We also provide policy recommendations to control emissions of Bitcoin mining based on the result of a more transparent and credible projection. We firstly use insights from the financial asset market as a proxy to estimate Bitcoin's future market capitalization. Previous studies that have examined Bitcoin's historical market performance, as well as transaction characteristics, suggest that Bitcoin is and has been developing prominently into a new asset class in the global financial market.[10],[11]

In addition to the insights from the financial asset market, our framework secondly builds on the competitive market feature of the Bitcoin mining industry. The Bitcoin mining industry has no entry restrictions but limited economies of scale, given constraints on the expansion of stable and low-cost electricity supply. Therefore, it has been observed that miners' rent is limited,[12] suggesting that the revenue from mining is close to the cost of mining in the long run. On the revenue side, the total revenue of Bitcoin mining in a specific year can be derived from the value of the Bitcoin mined plus fees paid for on-chain transactions. We assume that Bitcoin's long-term market capitalization growth rate falls within the range of historical growth rates of several comparable mainstream financial assets. On the cost side, we conclude that the electricity cost comprises a relatively stable share of total mining costs. Based on the total electricity cost, we estimate the electricity consumption for Bitcoin mining by assuming a specific electricity price (average price of \$0.05/kWh). We then utilize tailored emission factors—weighted by the geographical distribution of the hash rate using a unique dataset collected from mining pool operators—accounting for different decarbonization pathways of the electricity sector.

We estimate that the electricity consumption of Bitcoin mining is about 190 TWh in 2021, an amount close to the electricity consumed by all data centers worldwide in 2018,[13] while the network's electricity consumption could reach 7,500 TWh by 2100, about one-third of the world's total electricity consumption in 2018 (~22,000 TWh),[14] as shown in Figure 1. Bitcoin's carbon footprint, however, highly depends on the decarbonization rate of the world electricity sector. In a business-as-usual (BAU) scenario, cumulative CO_2 emissions from Bitcoin mining reach 30 gigatons by 2100, an amount as much as world total emissions in 2019 (~33 gigatons).[15] Under scenarios with higher decarbonization rates (450 and 550 (central case) scenario that implies 2°C and 3°C global warming, respectively), total emissions from Bitcoin mining would be around 1 $GtCO_2$ by 2100—a non-negligible number but not decisive to limit global warming.

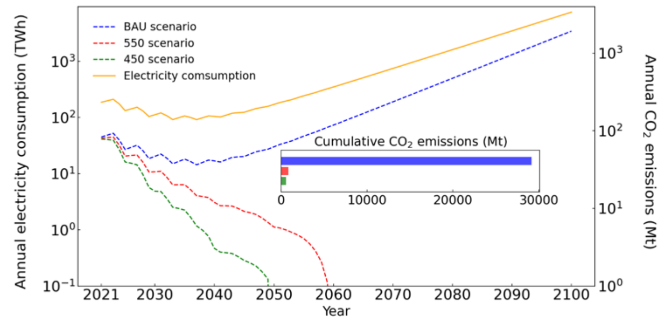

Fig. 1 | Annual electricity consumption and CO_2 emissions of Bitcoin mining through 2100. The business-as-usual (BAU) scenario assumes that the annual reduction rate of CO_2 emissions intensity of the world's electricity sector remains constant at 0.7%; the 450 scenario results in approximately 2°C global warming; the 550 scenario implies approximately 3°C global warming (for further details, see section 3.3 as below). Cumulative emissions under different scenarios are presented in the bar chart.

2. MATERIAL AND METHODS

2.1 Overview of the analytical framework

We use the year 2020 as the starting point of the timeline t in our analytical framework by setting $t = 0$ for 2020. We here estimate Bitcoin's current emissions in 2020, $E(0)$, and its cumulative emissions from 2021 ($t = 1$) through the year when the world electricity sector achieves carbon neutrality (we denote this year as T), E^T. We validate our analytical framework by comparing $E(0)$ to recent studies that estimate Bitcoin's annual emissions. Furthermore, we conduct a sensitivity analysis to demonstrate the impact of key parameters on E^T.

Bitcoin's cumulative emissions are the integration of its emissions in each year t, $E(t)$.

$$E^T = \int_1^T E(t)dt \tag{1}$$

Emissions in each year t can be calculated by multiplying the electricity consumption, $ELE(t)$, by the average emissions intensity (weighted by the geographical distribution of hash rate) of the world electricity sector in that year, $\overline{EF}(t)$.

$$E(t) = ELE(t)\overline{EF}(t) \tag{2}$$

Applying the assumption that the mining revenue $R(t)$ is equal to mining cost $C(t)$ and electricity price will remain stable in the long-term as p^{ELE} ($0.05/kWh based on our interviews with major miners in 2020. We have seen electricity price (constant price) remain relatively stable for the last few decades (5% change in 2000s compare to 1960s) in the United States[16]), the electricity consumption can be estimated by dividing the expenses on electricity in mining activities by the electricity price. The expenses on electricity in mining activities can be calculated using the share of electricity in total mining costs, α, which is a key parameter that we will discuss later and include in the sensitivity analysis.

$$ELE(t) = \frac{\alpha C(t)}{p^{ELE}} = \frac{\alpha R(t)}{p^{ELE}} \quad (3)$$

We consider two revenue streams of the mining activity: block rewards and on-chain transaction fees, shown in the equation below. The first term on the right-hand side represents the revenue from block rewards. It can be calculated by multiplying the scheduled number of Bitcoins to be mined in year t, $q(t)$, by the price of Bitcoin in year t, which could be estimated using Bitcoin's market capitalization in year t, $V(t)$, and all the Bitcoins mined until year t, $Q(t)$. The second term represents the revenue from on-chain transaction fees, which is the product of Bitcoin's market capitalization in year t, $V(t)$, and a ratio of on-chain transaction fees to market capitalization, β, which is discussed later.

$$R(t) = \frac{V(t)}{Q(t)} q(t) + V(t)\beta \quad (4)$$

For our main results, we assume that Bitcoin's market capitalization will grow from $V(1)$ in year 1 at a constant rate, γ, which is a key parameter that we discuss later and include in the sensitivity analysis. Bitcoins mined by year t is a pre-determined variable, which can be represented as the sum of Bitcoins mined by year 1, $Q(1)$, and all the Bitcoins mined from year 1 to year t, $\int_1^t q(t)dt$. Therefore, the mining revenue $R(t)$ can be rewritten as:

$$R(t) = \frac{V(1)(1+\gamma)^{t-1}}{Q(1) + \int_1^t q(t)dt} q(t) + V(1)(1+\gamma)^{t-1}\beta \quad (5)$$

Finally, we use different decarbonization scenarios of future average emissions intensity (weighted by the current geographical distribution of hash rate, assuming the distribution remains unchanged) of the world electricity sector in year t, $\overline{EF}(t)$. In the business-as-usual (BAU) decarbonization scenario, we assume the recent trend of annual reduction rate in the emissions intensity of the world electricity sector will continue. We adopt the annual reduction rate as 0.7% suggested by Knobloch et al.[17] for all the future years after 2020, and the world electricity sector cannot achieve carbon neutrality before the end of this century.

In two further decarbonization scenarios (450 scenario and 550 scenario), we consider faster decarbonization rates of the world electricity sector. We retrieve results for EMF27 analysis from integrated assessment models included in the IPCC AR5 Scenario Database (EMF27-450-Conv and EMF27-550-Conv) under the emission budget to stabilize CO_2 concentrations 450 and 550 ppm by 2100, respectively) with the trajectory of the world electricity sector's emissions intensity provided. We use the emissions intensity trajectory of the 550 decarbonization scenario for our main results (central case).

Combining all the equations above, Bitcoin's cumulative emissions for future years can be rewritten as:

$$E = \frac{\alpha}{p_{ELE}} \int_1^T V(1)(1+\gamma)^{t-1} \times \left[\frac{q(t)}{Q(1) + \int_1^t q(t)dt} + \beta\right] \overline{EF}(t)dt \quad (6)$$

2.2 Sensitivity analysis

To facilitate the sensitivity analysis, we use linear trends to fit emissions intensity trajectories, so emissions intensity beyond 2020, $EF(t)$, can be represented as the equation below, where θ is the annual decarbonization rate of the world electricity sector. For example, our main results use the 550 scenario, $\theta \approx 0.03$, which means the world electricity sector will become carbon neutral within roughly 33 years after 2020.

$$EF(t) = EF(0)(1 - \theta t) \quad (7)$$

Bitcoin's cumulative emissions for future years could be rewritten as:

$$E = \int_1^T E(t)dt = \frac{\alpha}{p_{ELE}} \int_1^T V(1)(1+\gamma)^{t-1} \left[\frac{q(t)}{Q(1) + \int_1^t q(t)dt} + \beta\right] EF(0)(1-\theta t)dt \quad (8)$$

We are interested in changes in Bitcoin's cumulative emissions for future years (E) relative to changes in the share of electricity in total mining cost (α), the annual growth rate of Bitcoin's market capitalization (γ), and the annual decarbonization rate of the world electricity sector (θ). We then compare the magnitude of each of the partial derivative.

3. RESULTS

3.1 Electricity consumption of future Bitcoin mining.

We find that the electricity consumption of Bitcoin mining will increase exponentially as transaction fees begin to dominate mining revenue. Figure 2 shows the trend of mining revenue and associated electricity consumption until the end of this century. Over the next decades, we expect electricity consumption to experience a phase of decline due to shrinking block rewards. Electricity consumption driven by block rewards decreases to less than 1 TWh by around 2075 compared to 170 TWh in 2021 and reaches zero by 2140. This trend changes around 2040 when electricity consumption begins to increase again due to increased on-chain transaction fees, which grows similarly to Bitcoin's market capitalization growth. By 2100, the annual electricity consumption reaches about 7.5 PWh, and continues to increase exponentially to about 160 PWh by 2140.

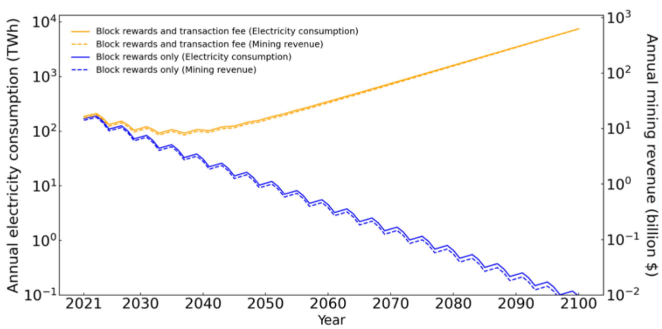

Fig. 2 | Mining revenue from block rewards and transaction fees and revenue from block rewards only, and their associated electricity consumption.

3.2 Carbon footprint of future Bitcoin mining

CO_2 emission factors of the electricity used for mining are needed to translate the electricity consumption into carbon emissions. We collect independent information on the geographic distribution of mining activities from mining pools for our estimates. We collect the hash rate and geographical distribution of all major mining pools (market share of > 10%), which together account for 70% of the total network hash rate (from January 2020 to September 2020). Figure 3a shows the network hash rate distribution as of September 2020.

Importantly, as 75% of the network hash rate originates from China, we further analyze the hash rate distribution among Chinese provinces. In particular, we find mining activities to be highly concentrated in regions with low-cost electricity, such as Sichuan and Inner Mongolia. Mining hotspots outside China include Kazakhstan and Russia. Figure 3b shows the CO_2 emissions intensity of electricity generation globally,[25] and by region for China.[26],[27] Based on these two data maps, we find the weighted average CO_2 emission factor of the electricity used for Bitcoin mining to be 0.45 kg/kWh as of 2020. The total CO_2 emissions we obtain for 2020 (63 megatons) are in line with existing research results.

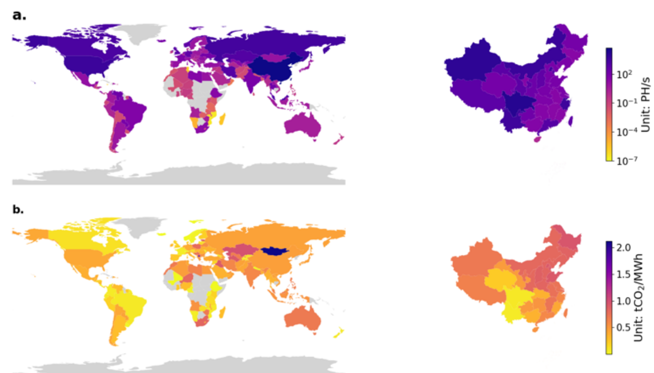

Fig. 3 | Hash rate geographic distribution (a) and emission factors of the electricity sector (b) for world regions and Chinese provinces. Geographic distribution of hash rate is provided by mining pool operators.

The projected carbon footprint of Bitcoin mining strongly depends on the decarbonization pathway of the electricity sector. Therefore, we project carbon emissions from Bitcoin mining under different decarbonization pathways. Under the BAU scenario, carbon emissions increase in line with electricity consumption. The cumulative emissions until 2100 (~30 gigatons CO_2) are as much as the world's total emissions in 2019 (~33 gigatons).[15] However, under the 450 and 550 scenarios with much faster decarbonization rates, annual CO_2 emissions from Bitcoin mining have peaked already around 2020 and gradually decline to zero by mid-century. This would lead to cumulative CO_2 emissions of 0.9 gigatons (550 scenario)—a non-negligible number but not decisive for climate goals (limiting global warming to below 2°C allows for approximately 1,000 gigatons CO_2 emissions from now on).

3.3 Sensitivity analysis

Assumptions for some key parameters used in our model's estimations substantially affect the results from our projected CO_2 emissions trajectories and Bitcoin's cumulative CO_2 emissions. These key parameters include the share of electricity in total mining cost, the annual growth rate of Bitcoin's market capitalization, and the annual decarbonization rate of the world electricity sector.

To demonstrate the sensitivity of our estimates relative to the above parameters, we first show in Figure 4 CO_2 emissions trajectories and cumulative CO_2 emissions until the world electricity sector achieves carbon neutrality under different parameter choices. We pick 50–70% as parameters for the share of electricity in total mining costs, 4–12% for the annual growth rate of Bitcoin's market capitalization, and 0.5–5% for the annual decarbonization rate of the world electricity sector. Changes in the annual decarbonization rate of the world electricity sector show a large impact on the emissions trajectory, while the share of electricity in total mining costs has a relatively small impact.

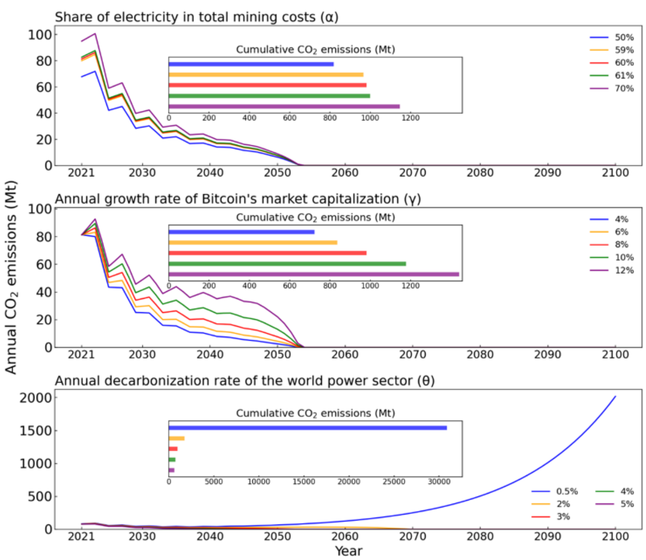

Fig. 4 | CO_2 emissions trajectories and cumulative CO_2 emissions of Bitcoin mining starting from 2021 under different parameter choices. We use 60%, 8%, and 3% for the share of electricity in total mining costs (α), annual growth rate of Bitcoin's market capitalization (γ), and annual decarbonization rate of the world power sector (θ), respectively, in our central case scenario.

4. DISCUSSION AND CONCLUSIONS

Our study provides a framework to analyze Bitcoin's future electricity consumption and carbon footprint. The proposed framework is not limited to Bitcoin but can also be applied to estimate the energy consumption and carbon footprint of other emerging technologies. This includes, for instance, additional cryptocurrencies[31], data centers[32], and communication infrastructures, given there is adequate information on the future size of the industry as well as the energy share in total production costs.

Our work also provides a baseline analysis for policymakers to address the (potentially) high carbon footprint of Bitcoin mining and discuss possible policy tools or mechanisms that ensure widespread emissions reduction from global mining centers. In particular, we focus the discussion on potential supply-side policy instruments that could reduce the share of electricity in total mining cost or enhance the annual decarbonization rate of the world electricity system. First, policies that effectively raise the price of electricity used for Bitcoin mining will directly reduce the quantity of electricity consumption for generating a unit value of Bitcoin. There are also significant indirect effects of higher electricity prices for Bitcoin mining, such as encouraging technical innovation of mining hardware, in response to raised electricity prices, which would result in a reduction of the share of electricity in total mining cost.[33] Second, economy-wide carbon pricing facilitates the dual effect of reducing Bitcoin's carbon footprint by both increasing the price of electricity and incentivizing the decarbonization of the electricity system. Third, direct R&D subsidies may enable further technical innovations in mining hardware, such as developing more energy-efficient integrated circuits (IC). In turn, the increase in IC efficiency would lower the total electricity demand and consequently reduce total electricity cost shares.

ACKNOWLEDGEMENT

This study has been supported by the National Natural Science Foundation of China (71974109 and 71690244). We thank Xiaomo Wang and Ziheng Zhu for their excellent research assistance.

REFERENCE

[1] Krause, M. J., & Tolaymat, T. Quantification of energy and carbon costs for mining cryptocurrencies. *Nature Sustainability*, **1(11),** 711–718 (2018).

[2] Stoll, C., Klaaßen, L., & Gallersdörfer, U. The Carbon Footprint of Bitcoin. *Joule*, **3(7),** 1647–1661 (2019).

[3] De Vries, A. Bitcoin's Growing Energy Problem. *Joule*, **2(5)**, 801–805 (2018).

[4] De Vries, A. Bitcoin boom: What rising prices mean for the network's energy consumption. *Joule*, *5*(3), 509–513 (2021).

[5] Jiang, S., Li, Y., Lu, Q., Hong, Y., Guan, D., Xiong, Y., & Wang, S. Policy assessments for the carbon emission flows and sustainability of Bitcoin blockchain operation in China. *Nature Communications*, 12, 1938 (2021).

[6] Mora, C. *et al*. Bitcoin emissions alone could push global warming above 2°C. *Nature Climate Change*, **8(11),** 931–933 (2018).

[7] Dittmar, L., & Praktiknjo, A. Could Bitcoin emissions push global warming above 2 °C? *Nature Climate Change*, **9(9),** 656–657 (2019).
[8] Masanet, E., Shehabi, A., Lei, N., Vranken, H., Koomey, J., & Malmodin, J. Implausible projections overestimate near-term Bitcoin CO2 emissions. *Nature Climate Change*, **9(9),** 653–654 (2019).
[9] Houy, N. Rational mining limits Bitcoin emissions. *Nature Climate Change*, **9(9),** 655.
[10] Liu, Y., & Tsyvinski, A. Risks and Returns of Cryptocurrency. *The Review of Financial Studies*, 1–39. (2020).
[11] Foley, S., Karlsen, J. R., & Putnins, T. J. Sex, Drugs, and Bitcoin: How Much Illegal Activity Is Financed through Cryptocurrencies? *Review of Financial Studies*, *32*(5), (2019).
[12] Prat, J., & Benjamin, W. An Equilibrium Model of the Market for Bitcoin Mining. *Journal of Political Economy*. (2021).
[13] Masanet, E., Shehabi, A., Lei, N., Smith, S., & Koomey, J. Recalibrating global data center energy-use estimates. *Science*, *367*(6481), 984–986 (2020).
[14] IEA. Electricity Information: Overview. https://www.iea.org/reports/electricity-information-overview (2019)
[15] IEA. Global CO_2 emissions in 2019. Retrieved from https://www.iea.org/articles/global-co2-emissions-in-2019 (2019).
[16] U.S. Energy Information Administration. Average Retail Prices of Electricity, 1960-2011. https://www.eia.gov/totalenergy/data/annual/showtext.php?t=ptb0810 (2020)
[17] Knobloch, F., Hanssen, S. V, Lam, A., Pollitt, H., Salas, P., Chewpreecha, U., Huijbregts, M. A. J., & Mercure, J. F. Net emission reductions from electric cars and heat pumps in 59 world regions over time. *Nature Sustainability*, **3(6),** 437–447 (2020).
[18] International Energy Agency. National electricity consumption and emissions in 2017. Retrieved from http://wds.iea.org (2020).
[19] Ministry of Ecology and Environment, China. Regional emission factors. Retrieved from http://www.mee.gov.cn/ywgz/ydqhbh/wsqtkz/201812/P020181220579925103092.pdf (2017).
[20] National Bureau of Statistics, China. Electric energy production in 2017. Retrieved from http://www.stats.gov.cn/ (2018).
[21] International Energy Agency. Emissions intensity for power sector in China in 2017. https://www.iea.org/reports/world-energy-outlook-2019 (2019).
[22] BTC.com. Blocks mined by mining pools. Retrieved from https://btc.com/stats/pool (2020).
[23] BitInfoCharts. Bitcoin fee in reward historical chart. https://bitinfocharts.com/comparison/bitcoin-fee_to_reward.html#1y (2020).
[24] Cambridge Bitcoin Electricity Consumption Index. Bitcoin Mining Map. Retrieved from https://cbeci.org/mining_map (2020).
[25] International Energy Agency. National electricity consumption and emissions in 2017. Retrieved from http://wds.iea.org (2020).
[26] Ministry of Ecology and Environment, China. China regional emission factors. Retrieved from: http://www.mee.gov.cn/ywgz/ydqhbh/wsqtkz/201812/P020181220579925103092.pdf (2017).
[27] National Bureau of Statistics, China. Electric Energy Production in 2017. Retrieved from http://www.stats.gov.cn/ (2018).
[28] Cambridge Centre for Alternative Finance. Cambridge Bitcoin Electricity Consumption Index. https://cbeci.org/ (2020).
[29] Digiconomst. Bitcoin Energy Consumption Index. https://digiconomist.net/bitcoin-energy-consumption (2020).
[30] Luderer, G. *et al*. Residual fossil CO2 emissions in 1.5-2 °c pathways. *Nature Climate Change*, **8,** 626–633 (2018).
[31] Gallersdörfer, U., Klaaßen, L., & Stoll, C. Energy Consumption of Cryptocurrencies Beyond Bitcoin. Joule, 4(9), 1843–1846 (2020).
[32] Koot, M., & Wijnhoven, F. Usage impact on data center electricity needs: A system dynamic forecasting model. Applied Energy, 291(March), 116798 (2021).
[33] Acemoglu, D., Aghion, P., Bursztyn, L., & Hemous, D. The environment and directed technical change. American Economic Review, 102(1), 131–166 (2012).