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Article

# Confronting the Carbon-Footprint Challenge of Blockchain

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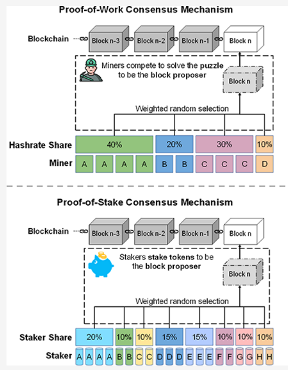
**ABSTRACT:** The distributed consensus mechanism is the backbone of the rapidly developing blockchain network. Blockchain platforms consume vast amounts of electricity based on the current consensus mechanism of Proof-of-Work (PoW). Here, we point out a different consensus mechanism named Proof-of-Stake (PoS) that can eliminate the extensive energy consumption of the current PoW-based blockchain. We comprehensively elucidate the current and projected energy consumption and carbon footprint of the PoW- and PoS-based Bitcoin and Ethereum blockchain platforms. The model of energy consumption of PoS-based Ethereum blockchain can lead the way toward the prediction of other PoS-based blockchain technologies in the future. With the widespread adoption of blockchain technology, if the current PoW mechanism continues to be employed, the carbon footprint of Bitcoin and Ethereum will push the global temperature above 1.5 °C in this century. However, a PoS-based blockchain can reduce the carbon footprint by 99% compared to the PoW mechanism. The small amount of carbon footprint from PoS-based blockchain could make blockchain an attractive technology in a carbon-constrained future. The study sheds light on the urgency of developing the PoS mechanism to solve the current sustainability problem of blockchain.




**KEYWORDS:** *$CO_2$ emission, energy consumption, climate change, blockchain, Proof-of-Stake mechanism*



## 1. INTRODUCTION

Since the blockchain concept was first proposed in Satoshi Nakamoto's paper,[1] it has rapidly evolved from a prototype concept into a popular technology. Blockchain technology has been proclaimed by many as the most significant technological breakthrough with the potential to transform most industries,[2] such as finance, health care, Internet-of-Things networks, video games, and others.[3,4] With the help of cryptographic hash functions, digital signatures, and distributed consensus mechanisms, the record in the distributed database can remove middlemen and establish trust between unknown parties.[1] For example, blockchain-based smart contracts can be partially or fully executed or enforced without human interaction when certain conditions are met. Blockchain-based digital currencies, another famous blockchain application allowing payment accessible to anyone in the world, had a total global market capitalization of over $2.5 trillion at its peak.

For all its benefits and forward-facing applications, blockchain uses the energy-intensive method of the Proof-of-Work (PoW) consensus mechanism to verify and validate transactions. The validation of ownerships and transactions is based on network participants adding valid blocks to the chain through solving puzzles involving hash functions.[5] A hash function transforms an input (such as text) into a fixed-length and fixed-structure string of bytes. The resulting output or value is known as a hash value or checksum. Any hash value generated from data using a particular hashing algorithm is always the same length and cannot be reversed; it is always one-way. Adding a block requires network participants to deploy computational resources to evaluate hash functions that require a certain amount of work. Because many active computational nodes are solving the same hash simultaneously, the total energy consumption is large, resulting in a heavy carbon footprint that has an enormous impact on the environment.[6] Mora et al.[7] claim that Bitcoin emissions alone could push global warming above 2 °C within less than three decades. Masanet et al.[8] have pointed out that the scenarios used by Mora et al. are fundamentally flawed and provided their three corrected scenarios that show Bitcoin could push global warming above 2 °C by 2100.

The accumulation of carbon dioxide ($CO_2$) in the atmosphere is the primary driver of global warming.[9] Human forcing of climate change is increasing the probability of severe ecological impacts[10] and the crossing of disaster tipping points.[11,12] According to scenario RCP 8.5 reported in Intergovernmental Panel on Climate Change (IPCC), without intervention, $CO_2$ emissions will rise from the current 49 $GtCO_{2eq}$/year to between 85 and 136 $GtCO_{2eq}$/year by 2050.[13] The rising $CO_2$ concentration could cause a global mean temperature change from the pre-industrial level (1880−1900) of 3.8 to 6.0 °C by 2100. The global annual carbon emission from Bitcoin and Ethereum mining was 43.9 megatons of $CO_2$ ($MtCO_2$) in 2017.[14−16] The energy

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consumption of blockchain is expected to grow significantly in the future due to the accelerated growth in the future.[7,8,17,18] Such growth has been observed based on the experience with other technologies, e.g., in the case of debit cards, stoves, and automobiles.

Proposed solutions to the carbon-intensive problem in blockchain include developing efficient hardware, reducing the difficulty required to resolve puzzles, or utilizing renewable energy. Each method has its own limitations; e.g., (1) A vicious circle limits the motivation for the innovation of more efficient equipment: the saved energy from the more efficient hardware may be employed to solve more puzzles for additional reward. The additional reward further incentivizes the purchase of more hardware to increase the mining hashrate and chances of higher rewards. Hashrate refers to the total combined computational power that is being used to mine and process transactions on a Proof-of-Work blockchain. It is an important metric for assessing the strength of a blockchain network. This situation may also cause other miners to follow the trend to purchase more hardware. (2) Reducing the puzzle difficulty may attract more computing power onto the network. (3) The production of renewable energy is subject to seasonality and may not meet the consistent power demand of blockchain.[19]

Here, we evaluate the current energy consumption and carbon footprint of PoW-based blockchain platforms and estimate the projected carbon footprint based on a new consensus mechanism, i.e., Proof-of-Stake (PoS). The PoS mechanism eliminates solving puzzles and thus dramatically reduces electric power consumption. Instead, in the PoS mechanism, the participants are selected by an algorithm for the right to validate blocks. With PoS, the probability of validating a block depends on the amount of stake a blockchain participant holds. The results of our model of energy consumption and carbon footprint from PoS-based blockchain demonstrate that the PoS mechanism can reduce carbon emissions by two orders of magnitude compared to the PoW mechanism. The migration from PoW to PoS may fundamentally solve the urgent energy-intensity problem in the blockchain system.

## 2. MODELING SECTION

**2.1. Proof-of-Work Consensus.** PoW-based blockchain, like Bitcoin, uses enormous amounts of energy to secure its network. Validation of blockchain by the Proof-of-Work consensus is computationally intensive. The PoW mechanism was first introduced in 1993 to combat spam emails[20] and was formally called "Proof-of-Work" in 1999.[21] This technology was not widely used until Satoshi Nakamoto created Bitcoin in 2009.[4] This mechanism could be employed to reach consensus between many nodes on a network and thereby secure the Bitcoin blockchain. However, the PoW mechanism works by employing many nodes to solve a cryptographic puzzle. The miner who first finds the solution receives a mining reward in the form of Bitcoin. The PoW consensus process is shown in Figure 1a based on previous studies.[22,23] The main drivers of the energy consumption of Bitcoin were found to be the geographical distribution of miners and the efficiency of the mining equipment.[24] de Vries proposed a market dynamics approach to evaluate the current methods for obtaining Bitcoin and estimated that it consumes 87.1 TWh of electrical energy annually as of 30 September 2019.[25] The energy consumption of Bitcoin is enough to power 9 million households in the US or the entire country of Belgium or Chile.[26] de Vries[27] also claimed the total network of Bitcoin could consume up to 184 TWh per year, with 60% of the miners' income going to pay for electricity at a price of $0.05 per kWh if the price of BTC is $42,000. For comparison, the current total annual electricity consumption is about 26,000 TWh in the world.

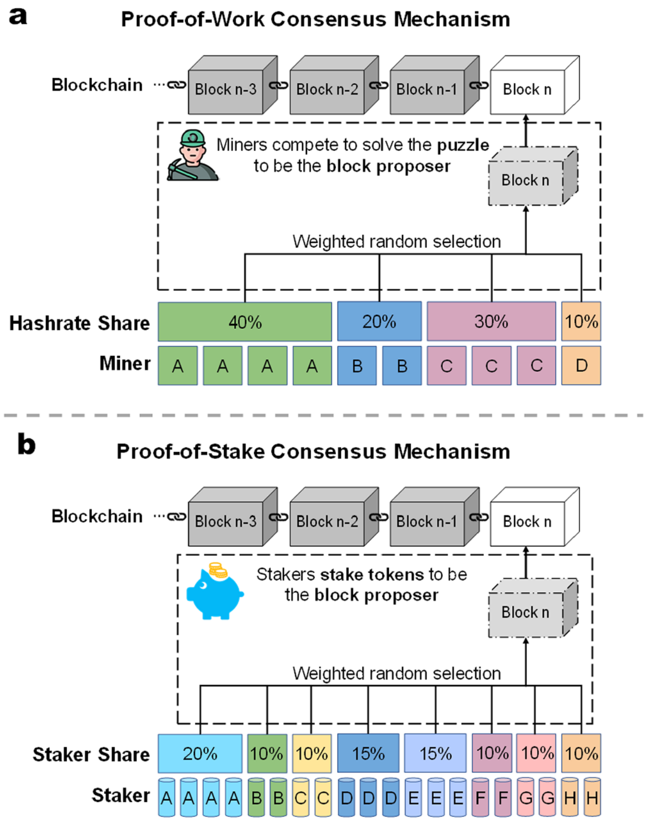


**Figure 1.** Comparison of (a) Proof-of-Work and (b) Proof-of-Stake mechanisms. With Proof-of-work (a), miners' computing powers compete against each other to complete transactions on the network and get rewarded. The hashrate share represents the share of the computing power owned by one miner occupying the total computing power of the whole network. If a miner manages to solve the puzzle, the new "Block *n*" is considered confirmed and connected to the previous block. Proof-of-Stake (b) is a proposed alternative to PoW. With Proof-of-Stake, the resource that is compared is the amount of share a staker holds. For example, someone holding 1% of the Bitcoin (share) can own 1% of the probability to validate the next block. Different PoS-based platforms have some differences in their algorithms. For example, the PoS of Ethereum is the underlying mechanism that activates validators upon receipt of enough stake. Users will need to stake 32 ETH (Ethereum tokens) to become a validator. Non-custodial liquid ETH staking protocols (e.g., Rocket-Pool) are available, which enable staking as little as 0.01 ETH. Thus, the entry barrier has been lowered considering infrastructures built around ETH 2.0. Another example is Algorand that was launched in 2019 by Dr. Silvio Micali[30] and his team from MIT. Algorand uses a unique variation of Proof of Stake called Pure Proof of Stake (PPoS). One ALGO coin is required to participate.[30] A PoS-based blockchain having more validators means a more secure and decentralized system.

**2.2. Migration from Proof-of-Work to Proof-of-Stake Consensus.** Eliminating the high energy consumption of blockchain is critical to its survival. In order to overcome the issues of energy consumption and low transaction speed, migration to the PoS mechanism is necessary to provide an effective path for the sustainable development of Bitcoin and


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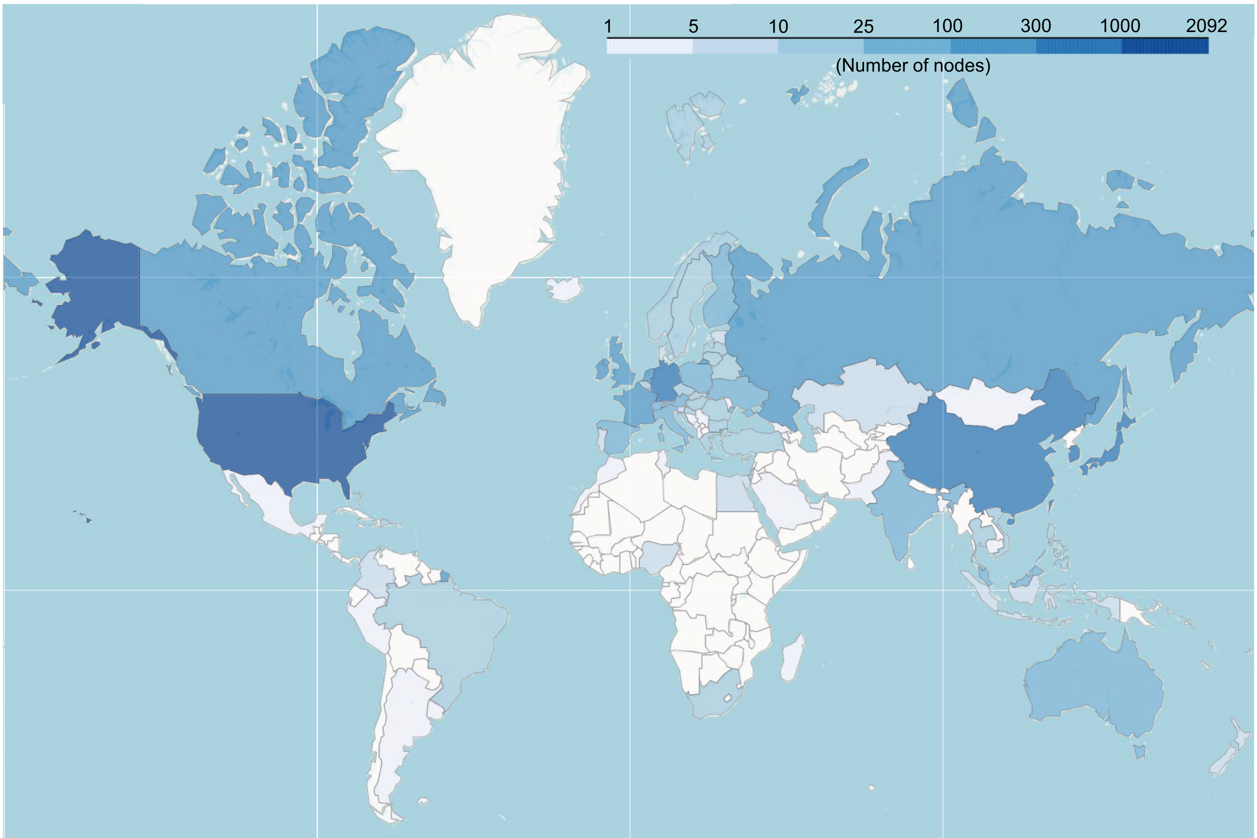


**Figure 2.** Geographical footprint of Ethereum 1.0 full nodes as reported in Data Sheet 2.1. This geographic footprint allows for an accurate estimation of energy consumption and carbon emissions as reported in Data Sheet 2.6.

other PoW-based blockchain platforms. There are various difficulties in migrating the PoW mechanism to the PoS mechanism on Bitcoin, such as a conflict of miner's interest. However, Bitcoin can be built on the PoS mechanism in theory; a potential way to do this could be to leverage the pre-existing full and light node network to implement a PoS style solution.

Ethereum[28] pioneers a plan for transition from the current energy-intensive and low-throughput PoW mechanism to a more robust, efficient, and energy-saving PoS mechanism. The migration process of Ethereum has been introduced in the Supporting Information. The success migration on Ethereum can be used as a reference for Bitcoin. Therefore, this study analyzes the architecture of the PoS mechanism on Ethereum and calculates the energy consumption and carbon footprint of both PoW and PoS mechanisms and provides the basis for Ethereum to deliver an accurate carbon footprint of its PoS mechanism. The mathematical model of the energy consumption of PoS-based Ethereum blockchain can lead the way toward the prediction of the energy consumption of other PoS-based blockchain technologies in the future.

**2.3. Proof-of-Stake Consensus.** The first Proof-of-Stake cryptocurrency, Peercoin,[29] was developed by Sunny King and Scott Nadal in 2012. The stake in the Peercoin network is coin age, i.e., network tokens times holding period. However, participants in the Peercoin network still need to solve a cryptographic puzzle, whose difficulty decreases with a higher coin age. Thus, the Proof-of-Stake consensus of Peercoin is a hybrid PoS/PoW. In the state-of-the-art PoS networks, the coin age is replaced by the number of network tokens a participant holds and the PoW puzzle is completely removed. Miners are replaced by stakers who lock up network tokens as stakes in the ecosystem. The proposers of the new block (who can receive the block reward) are selected based on their stakes in the PoS networks instead of their computational power in the PoW networks. Figure 1b shows the working process of the PoS mechanism.

**2.4. Modeling of Carbon Emissions of Blockchain.** Herein, we present a techno-economic model for determining the electricity consumption and carbon footprint of PoW-based Ethereum and Bitcoin. Researchers have established and calculated the energy consumption and carbon print of POW based blockchains. For example, Krause et al.[31] multiplied the daily hashrate by the energy consumption of a typical mining computer to quantify the power requirement of crypto network. This methodology can calculate the minimum energy consumption to produce one US dollar's worth of digital assets. Their results indicate that cryptomining consumed more energy than mineral mining to produce an equivalent market value. Fan et al.[32] calculated carbon footprints by an Environmentally Extended Multi-Regional Input−Output model. Their carbon emission account was obtained from GTAP10. Our analysis is based on mining revenue and hardware data for estimating energy consumption and carbon emission. Determining an accurate level of electricity consumption by Ethereum is unrealistic because of the great variety of graphics processing units (GPUs) used for mining.[33] Instead, we bracket the solution range with an upper and lower limit. The lower limit is defined by a scenario in which all miners use the most efficient hardware in each year,[31,34]


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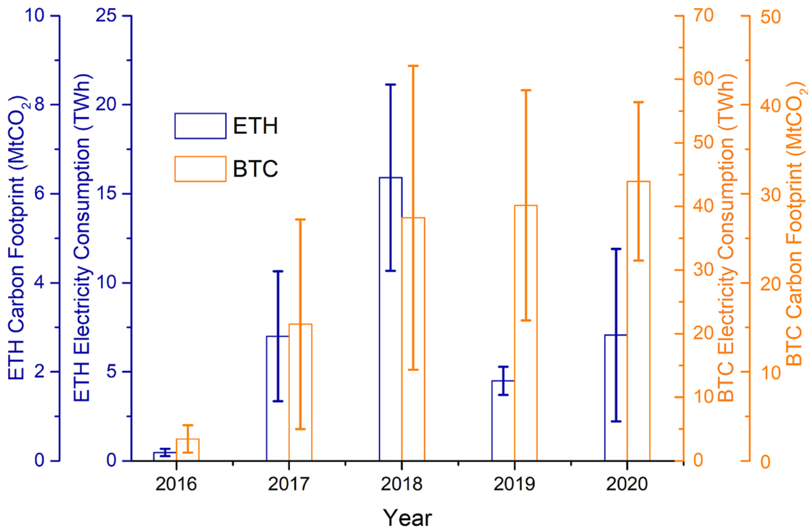


**Figure 3.** Annual electricity consumption and carbon footprint estimates of the PoW-based Ethereum on its lower limit and upper limit shown as royal blue color, and Bitcoin on its lower limit and upper limit is shown as orange color. Note that the weighted average emission factor electricity price, internet price, and energy intensity of each country and each year from 2016−2020 were used to calculate the electricity and carbon emission of Ethereum and Bitcoin blockchain. These numbers are reported in Data Sheets 2.2−2.6.

*2.4.1. Lower Limit.*

$$E_{\text{lower}}^{\text{PoW}}\ (\text{MWh}) = H\left(\frac{GH}{s}\right) \times e_{\text{ef}}\left(\frac{\text{J}}{\text{MH}}\right) \times 10^{-3} \times 24(\text{h}) \quad (1)$$

where $E_{\text{lower}}^{\text{PoW}}$ = power consumption of lower limit [MWh], $H$ = hash rate [GH/s], and $e_{\text{ef}}$ = energy efficiency of most efficient hardware [J/MH].

The upper limit is defined by the breakeven point of revenues and electricity cost. Rational behavior would lead miners to disconnect their hardware from the network as soon as their costs exceed their revenues from mining and validation.

*2.4.2. Upper Limit.*

$$E_{\text{Upper}}^{\text{PoW}} = [(R_{\text{B}}(\text{ETH}) + R_{\text{T}}(\text{ETH}) + R_{\text{U}}(\text{ETH}) + R_{\text{UI}}(\text{ETH})) \times M(\text{USD/kWh})]/[p_{\text{N}}(\text{USD/kWh})] \times \frac{1}{1000} \quad (2)$$

where $E_{\text{upper}}^{\text{PoW}}$ = average daily power consumption of upper limit [MWh], $R_{\text{B}}$ = block reward [ETH], $R_{\text{T}}$ = transaction fees [ETH], $R_{\text{U}}$ = uncle reward [ETH], $R_{\text{UI}}$ = uncle including reward [ETH], $M$ = market price [USD/ETH], $p_{\text{N}}$ = electricity price [USD/kWh].

The data is reported in Data Sheet 1.1.

The efficiency of the hardware is an essential parameter in determining energy consumption. The calculation details are introduced in the Supporting Information. Based on the geographical footprint of Ethereum nodes and the household electricity prices of the countries where nodes are located, the weighted average of electricity price and carbon emission factor of nodes can be calculated for those running on PoW-based Ethereum. The data and calculations are expressed in detail in the Supporting Information. Figure 2 shows the location of the nodes that are identified based on device IPs. The weighted average of the electricity price and carbon emission factor of nodes running on Bitcoin has been reported in Data Sheets 2.4 and 2.5.

A pseudo agent-based model of a blockchain system with PoS has been used to calculate the energy consumption.[35] Herein, a realistic model based on Ethereum's PoS mechanism is analyzed.

A typical staker setup on Ethereum 2.0 consists of one Beacon node program and multiple validator client programs running on a computer with Internet connection. Each validator client program requires a minimum stake of 32 ETH. On Ethereum 2.0, the computing cost of running the Beacon node program is identical to that of a full node program (e.g., Geth) on Ethereum 1.0.[36] The validator client program on Ethereum 2.0 plays a similar role as the miner on Ethereum 1.0. However, unlike miners on PoW-based Ethereum 1.0, the validator client program is resource-efficient, and its energy consumption is significantly less than that of the Beacon node program. As a result, the energy consumption of running validator client programs is assumed to be negligible.[37]

## 3. RESULTS AND DISCUSSION

**3.1. Energy Consumption and Carbon Footprint of PoW-Based Ethereum and Bitcoin.** Figure 3 shows annual electricity consumption and carbon footprint of Ethereum and Bitcoin. The figure shows that the annual electricity consumption/carbon footprint of the upper limit of Ethereum has increased from 0.67 TWh/0.32 $MtCO_2$ in 2016 to 11.91 TWh/5.15 $MtCO_2$ in 2020. The electricity consumption/carbon footprint of the lower limit follows the same trend as the upper limit, increasing from 0.27 TWh/0.13 $MtCO_2$ to 2.22 TWh/0.96 $MtCO_2$ from 2016 to 2020. The upper limit of Bitcoin has increased from 5.60 TWh/4.04 $MtCO_2$ in 2016 to 56.42 TWh/38.61 $MtCO_2$ in 2020. The lower limit of Bitcoin has increased from 1.31 TWh/0.63 $MtCO_2$ in 2016 to 31.50 TWh/13.61 $MtCO_2$ in 2020. Although the decrease in market price resulted in a reduction of electricity consumption in 2019 because of higher prices, the order of magnitude increase of energy consumption since 2016 has raised concerns about the sustainability of blockchain technology due to its rapidly growing carbon footprint.


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**3.2. Energy Consumption and Carbon Footprint of PoS-Based Ethereum.** The lower limit of the carbon footprint of Ethereum 2.0 is defined by a scenario in which all stakers use the energy-efficient Jetson TX2 module (5 W) to run Beacon node programs and validator client programs. This lower limit of annual energy consumption and its carbon footprint for Ethereum 2.0 comes out at 0.0396 TWh and 0.0171 $MtCO_2$, respectively. In this scenario, the calculated total number of Beacon nodes running on Ethereum 2.0 is 903,569 (see the calculation details in the Supporting Information).

The upper limit of the carbon footprint for Ethereum 2.0 is defined by a scenario in which all stakers use the Intel Xeon server[38] to run Beacon node programs and validator client programs, resulting in 0.3119 TWh and 0.1348 $MtCO_2$, respectively. In this scenario, the total number of Beacon nodes running on Ethereum 2.0 is 439,507. Given that the total number of full nodes on Ethereum 1.0 is less than 7000, the PoS-based Ethereum 2.0 is expected to be capable of achieving a significantly higher level of decentralization with a much lower carbon footprint than PoW-based Ethereum 1.0.

**3.3. Projected Carbon Footprints of PoW and PoS-Based Blockchain Platforms.** The future usage of blockchain is a topic of considerable discussion because it is a promising and revolutionary technology. Wide usage of blockchain would result in a large carbon footprint. The energy consumption of Ethereum and Bitcoin exceeds 88% of the energy consumption of the entire blockchain space;[14] therefore, we mainly consider Ethereum and Bitcoin in this section.

Blockchain usage has experienced accelerated growth (Supporting Information Figure S2), which is a typical pattern during the early adoption of broadly used technologies. Figure 4a shows trends in the adoption of broadly used technologies over time. To develop a scenario for blockchain we used the incorporation rate of 36 different techniques for which data are readily available, such as debit cards, stoves, automobiles, water closets, etc. (see details in Data Sheets 3.1 and 3.2). The inset in Figure 4a shows the historical adoption rate of ETH and BTC in the past 5 and 11 years, respectively. If PoW-based Ethereum were to follow the median growth trend observed in the adoption of these 36 technologies, the cumulative $CO_2$ emissions of this blockchain alone could warm the planet 0.26 to 0.43 °C by 2120, shown in Figure 4b. We conduct an uncertainty analysis on the impact of carbon emissions on global temperature. The correlation coefficient between carbon emissions and global temperature is from the temperature projections of 42 Earth system models developed for Coupled Model Intercomparison Project Phase 5 (CMIP5). The purple right $y$ axis shows a lower bound of uncertainty from carbon emission on temperature change, the orange right $y$ axis shows the average value on temperature change in CMIP5, and the green right $y$ axis shows the upper bound on temperature change. Figure 4d shows that the total cumulative $CO_2$ emissions of PoW-based Ethereum and PoW-based Bitcoin could warm the planet from 6.23 to 10.16 °C by 2120. Another logistic growth model and its accuracy to predict the carbon footprint of blockchain have been proposed in the Supporting Information. The development of Ethereum and Bitcoin is highly dynamic and sensitive. The two projection models shown heretofore prove a baseline of Life Cycle Analysis to show that current PoW-based blockchain systems consume

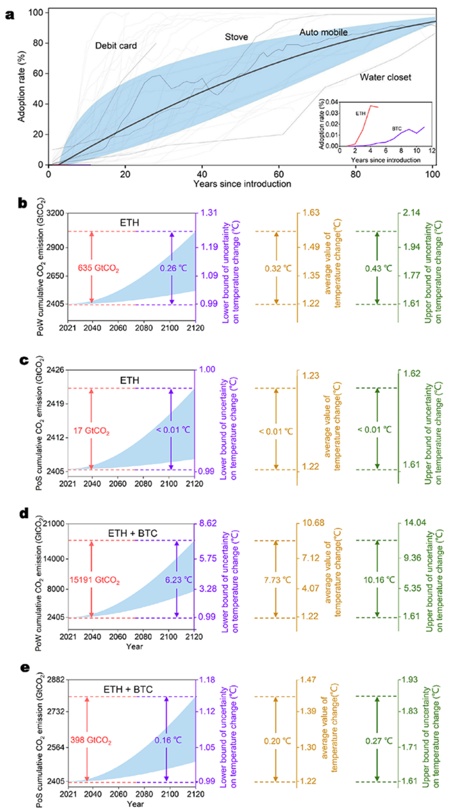


**Figure 4.** Projected carbon footprints of PoW and PoS-based Blockchain based on the adoption model. Panel (a) shows trends in the adoption of broadly used technologies documented in Data Sheet 3.1. The blue shaded area indicates the margins of the upper 75% and lower 25% quantiles, and the thick black line is the median tendency across technologies (see Data Sheet 3.1). Gray lines indicate trends for each of the technologies (see Data Sheet 3.2). The inset figure shows the adoption rate of ETH and BTC of its own development in the past 5 and 11 years, respectively. Panels (b) and (c) show the projected cumulative $CO_2$ emissions and the resulting temperature rise from PoW-based Ethereum 1.0 and PoS-based Ethereum 2.0, respectively, if they were to follow the average growth rate of broadly adopted technologies. Panels (d) and (e) shows the projected cumulative $CO_2$ emissions and the resulting temperature rise from PoW-based Ethereum 1.0 plus PoW-based Bitcoin and PoS-based Ethereum 2.0 plus PoS-based Bitcoin, respectively, under the average growth rate of the technologies shown in (a). We conduct an uncertainty analysis on the relationship between carbon emissions and the increase in global temperature. The purple right $y$ axis shows lower bound of uncertainty by carbon emission on temperature change, the orange right $y$ axis shows the average value on temperature change, and the green right $y$ axis shows the upper bound on temperature change. The data is shown in Data Sheets 3.1–3.8.

amounts of energy and their future energy cost could be exponentially higher.

The utilization and adoption of renewable energy can reduce carbon emissions to a certain extent. One estimate claims that 39% of energy consumption from Bitcoin mining stems from renewable energy.[39] However, this will not solve the overall sustainability problem of blockchain,[40] which is not limited to Ethereum and Bitcoin but shared by the whole blockchain industry. Given the decentralized nature of blockchain, its overall computing verification process of the overall system must migrate to the PoS mechanism in order to reduce the carbon footprint of Ethereum by 99%. Figure 4c shows that in


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100 years, the cumulative carbon emission from PoS-based Ethereum will be 17 $GtCO_2$, pushing the temperature to increase less than 3% compared with the carbon emissions from PoW-based Ethereum shown in Figure 4b. We can estimate the energy consumption of PoS-based Bitcoin in accordance with the mathematical model of PoS-based Ethereum established in the study. Figure 4d shows the carbon emission from PoS-based Ethereum and Bitcoin. The temperature increase from PoS-based Ethereum and Bitcoin can be reduced from 0.16 to 0.27 °C compared to 6.23 to 10.16 °C caused by PoW-based Ethereum and Bitcoin in 100 years at the case of the average value of temperature change. The energy consumption of different PoS-based blockchain platforms, such as Algorand[30] or Avalanche,[41] are different due to their altered algorithms, but the energy consumption of all PoS-based blockchain platforms can be reduced significantly in comparison to the PoW-based blockchain. There are other potential deployment methods with respect to blockchain for sustainable outcomes. For example, Delegated Proof-of-Stake (DPoS) and the "Delegated Byzantine Fault Tolerance" (DBFT) models use negligible amounts of energy to grant validating power to stake-holding nodes.[42]

Blockchain usage has experienced accelerated growth, which is a typical pattern during the early adoption of broadly used technologies. However, blockchain platforms are consuming vast amounts of electricity of 100 TWh yearly, enough to power the entire country of Netherlands or Finland. The energy consumption of PoW-based Blockchain is not sustainable in the future if all financial transactions were covered by blockchain. We could assume that the blockchain validation cost is proportional to the volume going through the system. Unfortunately, blockchains are not limited to financial transfer. If each ton of $CO_2$ sequestered needs its own blockchain entry, we will add tens of billions of additional entries. However, we think that this is small in comparison to all the other things that might have to be recorded and preserved in a ledger. Therefore, how to eliminate the high energy consumption of blockchain is of urgency to the global environment and critical to its survival.

The novelty and significance of the study is that we predict the energy consumption of PoS-based Ethereum based on its real mechanism for the first time and comprehensively elucidate the projected energy consumption of PoS-based blockchain in the future. The insights about Ethereum's PoS can be transferred to other blockchains using PoS. The mathematical model of energy consumption of PoS-based Ethereum blockchain can lead the way toward the prediction of energy consumption of other PoS-based blockchain technologies in the future. This paper provides a baseline Life Cycle Analysis (LCA) to show what the problem is and shows that new ideas in how to validate blockchains could reduce emissions by 2 orders of magnitude. The contribution of the study is that it quantifies these LCA analyses.

The study suggests that if the adoption rate of PoW-based blockchain follows other broadly used technologies or logistic growth models, it could create an electricity demand capable of producing enough $CO_2$ emissions to exceed 1.5 °C of global warming in three decades. The analysis of electricity consumption and carbon emissions elucidate that any further development of blockchain should shift toward the PoS mechanism to reduce the electricity demand by 2 orders of magnitude in an effort to mitigate global temperature rise below 1.5 °C. The migration from PoW to PoS mechanism will profoundly affect the energy consumption and sustainable development of blockchain.

## ■ ASSOCIATED CONTENT

### Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.est.2c05165.

Advantages and disadvantages of the Proof-of-Stake mechanism; calculation of energy consumption and carbon footprints of PoW-based ETH; migration of Ethereum from a PoW consensus mechanism to a PoS consensus mechanism; calculation of energy consumptions and carbon footprints of PoS-based ETH; projected carbon footprint of blockchain based on the logistic model; current trend of Ethereum and Bitcoin usage (PDF)

Data obtained from this study (XLSX)

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### Author Contributions

‡These authors contributed equally.

### Author Contributions

T.F.S., K.S.L., and V.B. supervised the project. X.S. conceived the idea. H.X. designed and carried out the model of PoS mechanism. X.S. and W.L. designed and carried out the model of PoW mechanism. X.S., W.L., and K.S.L. designed and performed the models of projected carbon footprint. X.S., H.X., and W.F.L. analyzed the data. V.B. contributed to the analysis of PoW and PoS architectures of blockchain. K.S.L. and T.F.S. analyzed the impact of carbon footprint and energy consumption from PoW and PoS-based blockchain. X.S., K.S.L., T.F.S., V.B., and H.X. wrote the manuscript. All authors


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contributed to the results discussion and manuscript preparation.

### Notes

The authors declare no competing financial interest.

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