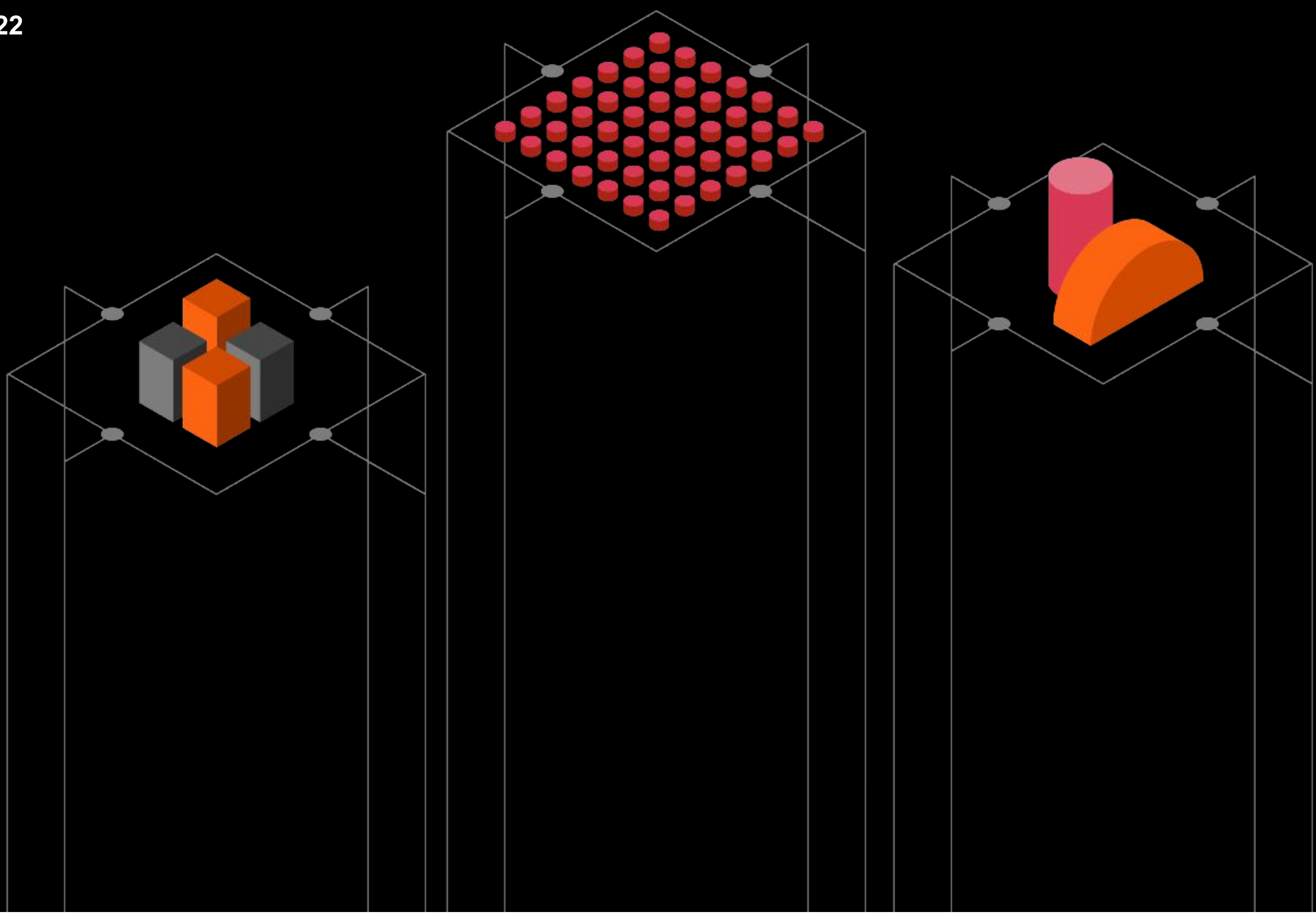
Embracing sustainable blockchain innovation: Understanding the impacts of blockchain technology

Fall 2022



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Stellar Development Foundation

Purpose of report:

The purpose of this report is to provide a detailed, step-by-step technical methodology and subsequent results of PwC's Blockchain Sustainability Framework developed for the Stellar Development Foundation. It will cover:

1. Why this framework focuses on the three impact areas highlighted: energy use, carbon emissions, and embodied carbon
2. The technical methodology used for each of these impact areas, including relevant metrics and measurement approaches
3. The overall results from the analysis.

Table of contents

Executive summary

Blockchain technology has the potential to be transformational for the global financial system. Unfortunately, blockchain gained a reputation as a potential environmental risk due to broadly-stated headlines about its energy-intensive mining processes. However, a deeper analysis of blockchain technologies revealed that blockchain protocols are not the same, and each may have varying levels of environmental impact. Thorough research and analysis is needed to inform the decisions of regulators, users, and the market as various blockchain networks are scaled. This report presents a framework to assess the environmental impact of a subset of blockchain protocols.

The Stellar Development Foundation (SDF) commissioned PwC to develop a framework (“the Framework” or “PwC’s Blockchain Sustainability Framework” or “BSF”) to evaluate the environmental sustainability of blockchain protocols and apply the Framework to benchmark the environmental footprint of multiple blockchain networks, including the Stellar network. In addition to a current state impact analysis, this report compares fundamental differences between blockchain networks, considers how blockchain sustainability may evolve in the future, and provides methodologies, which interested parties may use in their own evaluations.

Prior to the development of the Framework, a review of similar studies was conducted to understand the landscape of past analyses. Based on an evaluation of both stakeholder importance and feasibility of measurement, **it was determined that for the Framework, energy use and greenhouse gas (GHG) emissions (CO_2e) would be the primary metrics of quantitative assessment**, with additional qualitative considerations for e-waste and embodied carbon. See Figure 1 below for an illustration of the topic rationalization.

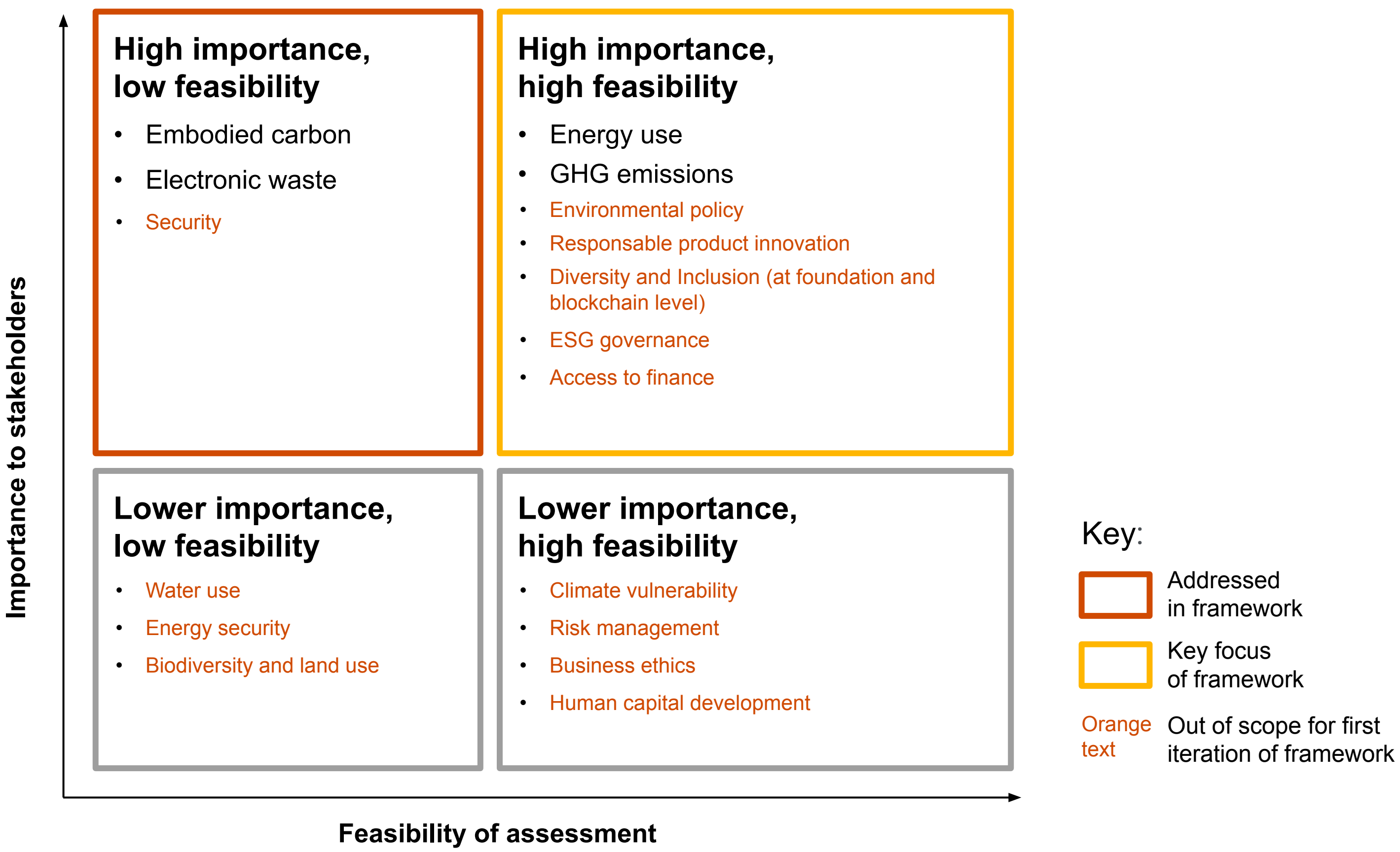


Figure 1. Matrix of stakeholder importance and assessment feasibility for each ESG factor identified.

(Note: Figure 1 illustrates examples of the different levels of importance and current feasibility of assessment).

To assess the environmental factors noted in Figure 1, an understanding of blockchain network architecture is important. At its core, a blockchain is a digital distributed ledger of transactions on a peer-to-peer network. Network participants, known as "nodes", are devices that record, verify, and store a database of transactions. Nodes must be in mutual agreement on each set of transactions occurring on the network to reach consensus on the state of affairs.

Given the decentralized nature of blockchain nodes, a defined approach is required to enable integrity and allow participants to come to an agreement on the validity of one another's transactions. These approaches to reaching agreement on a shared ledger are called **consensus mechanisms**.

Implementations of consensus mechanisms vary between blockchains depending on protocol design, as does the system power necessary for nodes to operate and maintain the ledger. Different use cases necessitate different approaches to consensus for distributed systems. The goal of the Framework is not to imply which consensus mechanisms might be better overall, but rather to build methodologies that can apply to similar implementations.

The Framework focuses on three broad categories of consensus mechanisms: proof-of-work (PoW), proof-of-stake (PoS), and Federated Byzantine Agreement (FBA), as described in Table 1 below. While these groupings represent three of the most prominent approaches, it should be noted that there are other types of consensus mechanisms which do not fall into these three broad categories, and some which share characteristics of more than one category.

	Proof-of-Work (PoW)	Proof-of-Stake (PoS)	Federated Byzantine Agreement (FBA)
Summary of approach	Network nodes who validate blocks on the network (often nicknamed "miners") are financially rewarded for **working** to win the competition to discover a valid cryptographic hash, the results of which are used to validate a transaction.	Validators are often required to commit a **stake** (for example, some minimum amount of currency). Validators are often selected to validate transactions based on a pro-rata share of their staked tokens, and may be at risk of losing a portion of their stake for misbehaving.	A quorum-based **Byzantine** agreement protocol, individual validator nodes maintain consensus through trusted relationships with other participants. Once enough validators agree on a transaction, they collectively validate the transaction.

Table 1. Summary of block validation approaches based on consensus type.

(Note: This overview of consensus mechanisms is not comprehensive.)

To assess the impact of the blockchain protocol, analysis is focused on components of a blockchain transaction that deviate from traditional payments infrastructure and vary between consensus types. The Framework does not consider upstream impacts, such as the production of validating hardware, nor does it consider the impacts of the developers creating the software, both for reasons of feasibility and limited variation. The analysis also excludes the impacts of the physical point of sale, cryptocurrency wallets, applications, and "layer 2" systems used for scalability of blockchain networks as these have been judged to be outside the scope of a core protocol assessment. Further rationale is explained in Section 3.1.2.

As such, the Framework aims to quantitatively address the environmental impacts of powering the consensus mechanism and data transmission/storage of a blockchain protocol. Figure 2 illustrates a summary of the in-scope components within the bounds of a typical blockchain transaction.

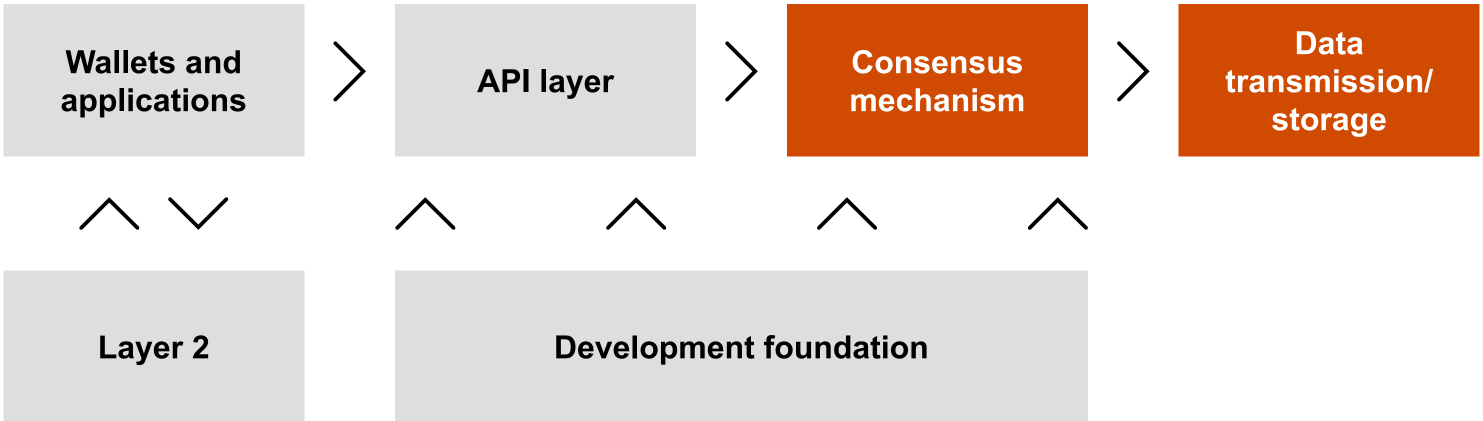


Figure 2. Simplified view of a blockchain transaction with in-scope components highlighted.

For the purposes of the Framework, sustainability metrics are calculated differently based on the class of consensus mechanism under evaluation, as each implementation has varying levels of measurability. Energy use of a blockchain protocol can be assessed by **estimating** energy requirements based on key data points or **directly measuring** the energy consumption of system participants. Further, a **"top-down" or "bottom-up"** approach of estimation or direct measurements may be employed.

Using the top-down method, calculations aim to capture the energy consumption of running the protocol and apply the total to the number of participating nodes. In essence, the process relies on attaching a wattmeter to a computer and measuring energy use of the entire node.

The bottom-up approach involves measuring energy use at the component level (e.g., using an interface built into the processor to measure energy consumption of various power domains within the CPU). In a bottom-up approach, the individual hardware components, such as CPU, memory (RAM), storage (disk), and networking, are measured or referenced and applied across the network.

The bottom-up approach is preferable as the estimate of energy consumption implicitly includes energy consumption associated with data transmission (i.e., the network adapter on the computer, as well as upstream energy use by the network operator). By disaggregating the drivers of energy consumption, the energy use calculation avoids double-counting energy use for network adapters. Disaggregation is also helpful in providing insights into the drivers of energy use and thus assists with the qualitative analysis of how future emissions might change.

Four distinct methods of calculating blockchain network energy consumption are classified in Table 2 below.

Estimated energy consumption: top-down	Economic estimates of energy use	Direct energy measurement: top-down	Direct energy measurement: bottom-up
Multiply the network hashrate (PoW) or number of active nodes (PoS/FBA) with energy use of a reference piece of hardware.	Approximates energy consumption based on the value of mining revenue. Based on an assumption that individual miners are economically rational actors.	Measure the real-world energy use of running the protocol, and multiply by the number of active nodes.	Assess energy use at the level of specific hardware components (e.g., CPU, memory, network, etc.)

Table 2. Taxonomy of energy use calculation methods.

In the Framework, proof-of-work (PoW) blockchains are evaluated using economic estimates of energy use, whereas proof-of-stake (PoS) and Federated Byzantine Agreement (FBA) blockchains are evaluated using a direct energy measurement (bottom-up) approach.

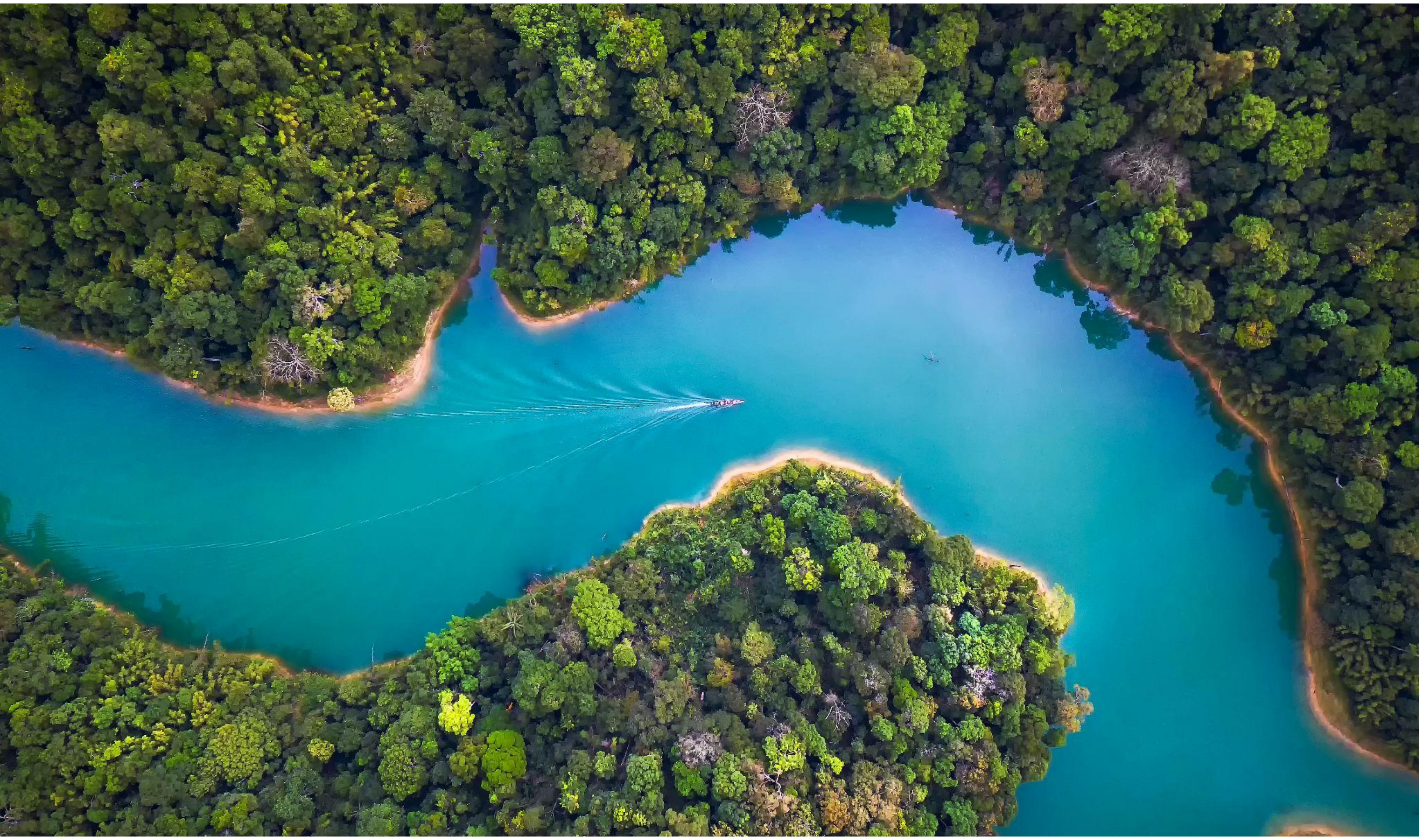
The latest calculation methodology from Cambridge University's Bitcoin Electricity Consumption Index is adapted and used to assess electricity consumption of PoW blockchains [1]. Infrastructure data for PoS and FBA-based blockchains may be obtained directly from active nodes or by referencing hardware requirements. For the quantitative analysis of the Stellar network below, data was obtained as a direct extract from the Stellar Development Foundations' operational nodes and Horizon API clusters. A previous community survey of Stellar validators indicates that Stellar nodes, regardless of administrator, are comparable in hardware and network transmission [2].
Data received from the Stellar Development Foundation were collected between February 7, 2022 and March 9, 2022.

The results of the analysis are summarized below.

Program	Estimated yearly electricity use (kWh)	Electricity use per transaction/API request (Wh/txn)	Estimated yearly emissions (kg CO_2e/yr)	Emissions per transaction/ API request (g CO_2e/txn)
Stellar Core	261,435	0.173	94,098	0.062
Horizon API	219,889	0.000229	85,181	0.0000886

Table 3. Results of electricity use and carbon emissions from electricity for Stellar Core and Horizon API, part of the Stellar Network.

(Note: Calculations are based on node types required for the ongoing operation of the protocol. Transaction types and node types may vary.)



Observations and Discussion

Prior to discussing observations from the results of the research, it should be noted that sustainability is only one component in the overall assessment of a blockchain protocol. Scalability, security, and decentralization are other core features to consider in a blockchain protocol. Furthermore, users may value smart contract compatibility, privacy, or extremely fast transaction time over other considerations. As such, the results of this report should be considered in the greater context of the utility of the platform being used.

Based on the methodology and outcome, several observations can be drawn:

Sustainability should be a core value of emerging blockchain technology developers: It is important to establish methods to assess the sustainability of new technologies as they develop to help guide them so that as they grow they do not ock in adverse impacts.

Blockchain technology does not necessitate the high environmental burden that some may perceive it to. Some blockchains generally require more energy to function, but it may be a tradeoff for higher security, scalability, or decentralization. The usefulness of different consensus mechanisms is ultimately a subjective and ongoing conversation among industry participants, and each protocol has unique advantages that should not be discounted.

Blockchain may offer benefits to aspects of the existing financial system without an environmental trade-off. For example, blockchain networks can provide near-instant transaction settlement, open and transparent international trade, and smart contract capabilities, at a potentially reduced environmental footprint when compared to legacy financial processes. The total impact of these blockchain solutions is dependent on the technology stack that is selected and the type(s) of energy sources, which can be estimated using the methodologies in the Framework. It should be noted that blockchain is not necessarily replacing legacy financial systems, but rather can be used to augment them with new capabilities.

There are additional sustainability and broader ESG indicators to consider for potential future quantification. This report focused primarily on two metrics that were of high importance and high feasibility for measurement: electricity use and carbon emissions. Future research can consider quantifying the impact of some or all of the following: embodied carbon, electronic waste, environmental policy, water use, energy security, or biodiversity and land use. Further, broader social and governance impacts may be considered—these could include measurements for global financial inclusion, governance and risk management, business ethics, or responsible product innovation.

Immediate actions can be considered by market participants to estimate and mitigate their environmental impact. Market participants can continue efforts to source energy directly from renewables and to improve overall response to energy demand (see Sections 5.1.2 and 5.1.3). Blockchain networks and corporations alike should continue to seek to reduce their energy consumption in the near term and incorporate environmental considerations into how they engineer future iterations of blockchain protocols and the applications built on top of them. One other action that may be taken to reduce environmental impact is to offset calculated emissions with purchases of high quality carbon credits or Renewable Energy Credits (RECs), as described in Section 3.2.4 of the report.

Blockchain technology is expected to grow at a rapid pace, and blockchain networks' percentage of total energy consumption may depend heavily on the changes that they may be able to make regarding energy consumption. Given the value that many of these blockchain networks provide and are likely to provide in the future, any future regulation decisions regarding blockchain protocols should be considered in the context of the value they bring and the impact they can have relative to other technologies.

This report can be used to shed light on the energy and emissions measurements, but does not speculate on the relative value of one blockchain protocol against another. Market participants should continue to make choices that can benefit their own interests and that of the environment around them—this means continuing to balance the tradeoffs of decentralization, scalability, security, and sustainability.

Blockchain is a constantly evolving technology. Its decentralized nature promotes ongoing innovation, which can be seen in the unique differentiation between protocols. There are a number of assumptions which were made to make this analysis possible (see Section 3) and several boundaries to the research and outcomes (see Appendix 1).

Context: Blockchain Technology and Sustainability

Blockchain technology has attracted significant attention over recent years. Harnessed thoughtfully and responsibly, it has the potential to offer many benefits through shifting traditional economic systems and enabling innovations. Its rapid dissemination, however, raises a host of complex questions and broad concerns about how the technology will potentially affect society and the planet.

1.1. Growth of blockchain technology

Blockchain technology adoption has grown rapidly over the past decade, with further acceleration in the past few years. Investment into the development of blockchain solutions and rising cryptocurrency values created a positive feedback loop, leading to the creation of more use cases, specialized chains, and dApps (decentralized applications) which continue to bolster the growing interest, adoption, and scaling of solutions.

To better understand the reason for the growth of blockchain technology, it is useful to know what problems it is solving and what its use cases are. Cryptocurrencies, one of the earliest applications for value exchange on blockchains, allow for irreversible, transparent transactions that can occur instantaneously between global entities.

Blockchain technology also allowed for enhanced asset provenance. In combination with the Internet of Things (IoT), blockchain can assist with transparent traceability of items in both the physical and digital world. This can apply to elements of a supply chain across multiple industries—healthcare, retail, aerospace and defense, and many others.

Given the immutable nature of blockchain technology, it can also prove digital ownership for anything from art to identities. Digital identities can be stored using cryptographically secured, decentralized data storage systems in order to maintain control over which part (if any) of their identity is revealed to others. In the case of loss or theft of physical or digital documentation, users can retain their identifying information in a trusted manner.

Moreover, smart contracts enable a plethora of new use cases. Smart contracts are programmatically executable contracts that automatically trigger based on pre-approved conditions. For example, a mortgage payment can be automatically executed based on the day of the month, or an IoT device could be triggered to action based on feedback from a blockchain smart contract. The power of smart contracts has even led to innovations such as Decentralized Autonomous Organizations (DAOs), which are self-governing organizations enabled by the technology, and non-fungible tokens (NFTs) that link digital assets and their ownership.

Technology convergence will continue as companies and individuals strive to solve problems using novel solutions. Web3, a term used to describe a forthcoming iteration of the internet rooted in blockchain technology, is commonly cited as containing several emerging technologies such as artificial intelligence (AI), blockchain, virtual reality (VR), augmented reality (AR), and internet of things (IoT). $25.2B of venture capital funding was invested into blockchain technology startups in 2021, up more than 700% from 2020 [3]. Venture funding hit new highs each quarter of 2021, primarily driven by growing consumer and institutional demand for crypto. Blockchain funding made up 4% of global venture spend, up from 1% in 2020.

1.2. Blockchain's impact on sustainability and the race to net zero

PwC's Global Blockchain Impact Report estimates that blockchain's total global impact will be equivalent to 1.4% of GDP in 2030 [4]. While the economic impacts of blockchain are projected to be significant, so too is its sustainability impact, at least for certain use cases. Some of the most popular applications of blockchain are extremely compute-intensive, consuming significant amounts of energy and potentially generating high levels of greenhouse gas (GHG) emissions that impact the world's climate.

This large and rising energy use runs counter to the ambition of many countries and organizations to reach a state of so-called "net zero" GHG emissions by mid-century. Following two decades of talks, this goal was codified in December 2015, when 195 governments came together to sign the Paris Agreement. Signatories pledged to pursue efforts to limit global warming to well below 2°C, preferably to 1.5°C [5]. This was further cemented in 2021 at the COP26 conference in Glasgow, where nations' efforts to decarbonize were solidified via various commitments [6].

It is projected that to mitigate the worst impacts of climate change, the world needs to cut emissions by 45% by 2030, and reach "net zero" by mid-century [7]. However, it is becoming evident that current global decarbonization action is nowhere near enough. Research suggests that a 12.9% annual global rate of decarbonisation is now required to limit warming to 1.5° C, more than five times the rate achieved in 2020 [8]. Critical to global decarbonization and achievement of net zero is aiming to shift the world to fully renewable energy generation and use. Accompanying this, more efficient use of energy across the economy and society could make the climate challenge easier to manage. There are meaningful shifts in policy, investment, and customer sentiment that are helping encourage further decarbonization.

Policy	Investors	Customers
70+	**35%**	**21%**
countries, covering 76% of global emissions, have set net zero targets [7]	of AUM have committed to 2030 emissions targets and net zero by 2050 or sooner [9]	Of the largest 2,000 public companies have committed to net zero targets, forcing peers and suppliers to adapt [10]

1.3. Progress in driving sustainability considerations in the blockchain community

The sustainability impact of blockchain attracted extensive media coverage given the high energy impact of some of its most prominent use cases and the proliferation of third-party impact assessments given the transparency of its data.

Blockchain and consensus mechanisms: a primer

What is blockchain?

A blockchain is a decentralized ledger of all transactions across a peer-to-peer network. Using this technology, participants can confirm transactions without a need for a central clearing authority.

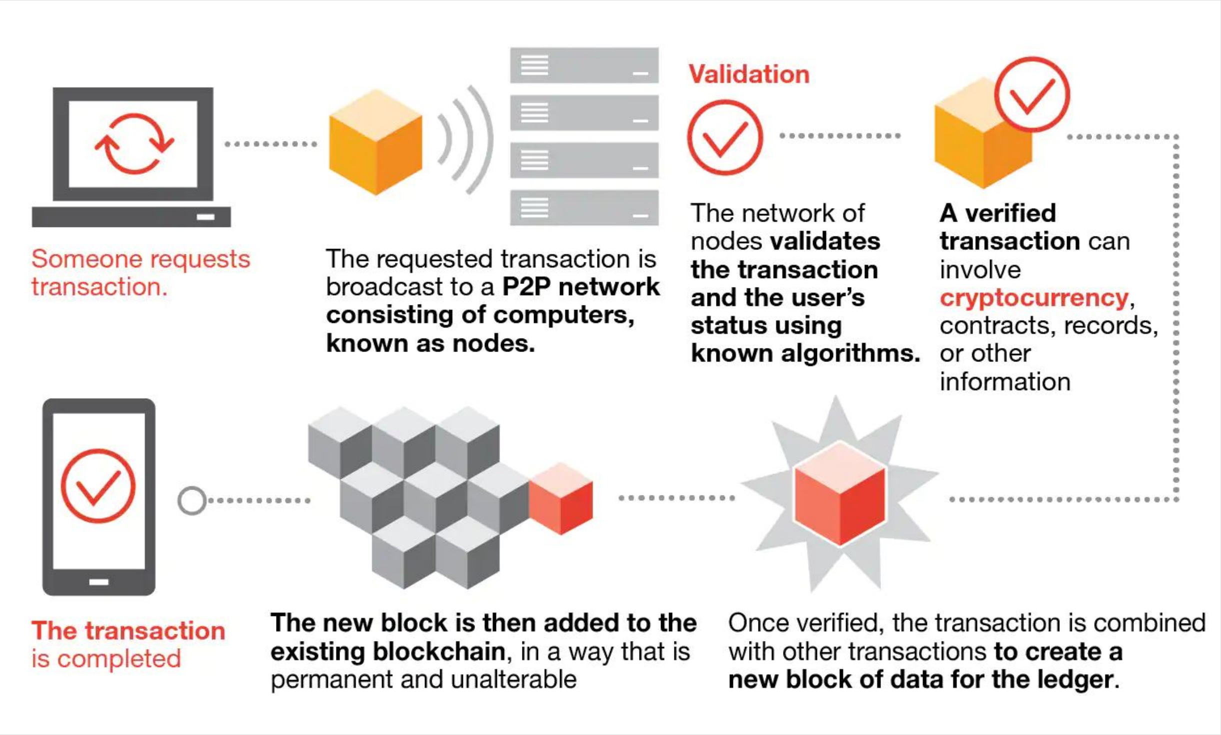


Figure 5. Step-by-step process flow of a blockchain transaction. Source: PwC

What is a consensus mechanism, and what types of mechanisms exist?

Given the decentralized nature of blockchain, a defined approach is required to enable integrity by allowing participants to come to an agreement on the validity of one another's transactions. These approaches to reaching agreement on a shared ledger are called consensus mechanisms.

The first foray into blockchain consensus was introduced with the conception of the Bitcoin blockchain. This consensus mechanism, known as proof-of-work (PoW), relies on the computational power of distributed nodes to hash blocks of transactions onto an ongoing chain of events. Alternative blockchain consensus mechanisms also exist, such as proof-of-stake (PoS) and Federated Byzantine Agreement (FBA), each with their own characteristics and benefits. These are summarized in Table 5 below.

	Proof-of-Work (PoW)	Proof-of-Stake (PoS)	Federated Byzantine Agreement (FBA)
Summary of approach	Network nodes who validate blocks on the network (often nicknamed "miners") are financially rewarded for **working** to win the competition to discover a valid cryptographic hash, the results of which are used to validate a transaction.	Validators are often required to commit a **stake** (for example, some minimum amount of currency). Validators are often selected to validate transactions based on a pro-rata share of their staked tokens, and may be at risk of losing a portion of their stake for misbehaving.	A quorum-based **Byzantine** agreement protocol. Individual validator nodes maintain consensus through trusted relationships with other participants. Once enough validators agree on a transaction, they collectively validate the transaction.

Table 5. Summary of block validation approaches based on consensus mechanism classification.

(Note: This overview of consensus mechanisms is not comprehensive.)

As governments move to enact policies which curb emissions to meet their climate targets, they are increasingly concerned with the impact of business and technology on the climate. With the significant investment growth and new entrants to the blockchain ecosystem, considerations of impact beyond technological innovation or return on investment are rising.

Creators of blockchain innovations should consider the sustainability of their solutions and stakeholder demand for transparency on these impacts will likely continue to rise. The blockchain ecosystem has begun to respond through initiatives to reduce its negative impacts and create new positive impacts. For example, the World Economic Forum has launched the Crypto Impact and Sustainability Accelerator (CISA) alongside CoinDesk that is aimed to enable crypto-ESG efforts [11]. The interest in sustainable blockchain solutions appears to be increasing, signaling that sustainability is a key industry consideration (primarily environmental sustainability).

Interest in blockchain and sustainability

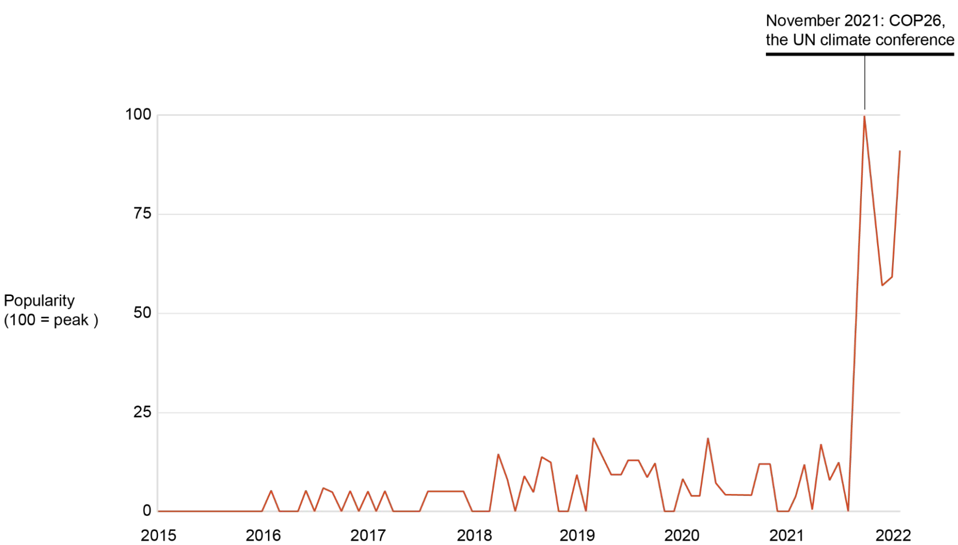


Figure 6. Popularity score for blockchain and sustainability over time [12]. Source: Google Trends.

2.1. Challenges of comparing blockchain protocols

As discussed in Section 1, the consensus mechanism of a blockchain protocol is the critical component for achieving agreement on network state. Consensus mechanisms have been adapted over time as benefits and drawbacks have been identified within each approach, and thus serve as a leading differentiator between protocols. This leads to a focal point of discussion for blockchain protocols: The Blockchain Trilemma.

Well known in the industry, the Blockchain Trilemma proposes a set of three main issues—decentralization, security, and scalability—and postulates that a blockchain protocol can only reliably provide two of the three, sacrificing one as a trade-off. It is important to note that the Trilemma is a conceptual model for a challenging problem within the blockchain space, but does not suggest that it is impossible to solve. As emergent protocols seek solutions to address the Trilemma, creators should also consider a fourth axis of sustainability, or how the protocol impacts the environment.

The Blockchain Trilemma

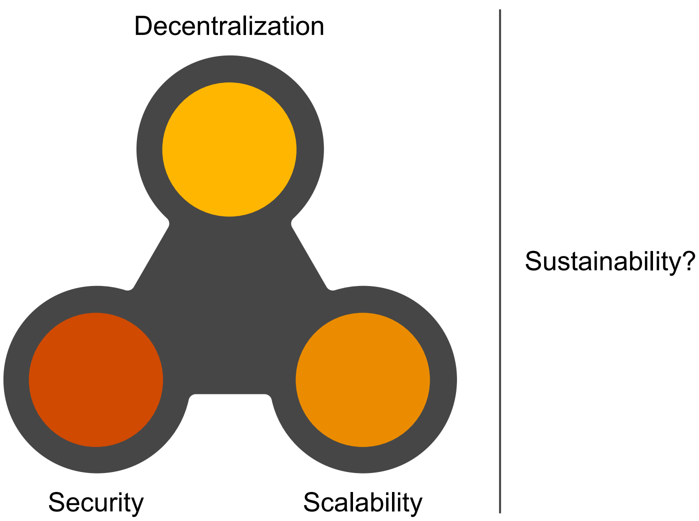


Figure 7. The core components of the Blockchain Trilemma.

Due to the decentralized nature of blockchain systems and the vast number of anonymous participants, it is not feasible to retrieve energy usage data for each participant in a given protocol. However, attempts can be made to estimate the environmental impact of blockchains through a variety of approaches, which are covered in the remainder of this report.

2.2. Purpose of the Framework

The Framework aims to provide a methodology to quantify the environmental impacts of a blockchain protocol. Although existing studies on the sustainability of blockchain exist, these often focus on a single blockchain protocol and define bespoke methodologies and assumptions, making meaningful comparisons of results across studies challenging. By defining a consistent and widely applicable methodology, as well as a common set of assumptions and data sources, the Framework can theoretically be applied to a wide range of blockchain protocols while providing comparable and trusted results.

The methodology described in this document can be repeated regularly to follow the changing impacts of blockchain protocols as they evolve. As such, reporting cadences can be established to maintain transparency and track growth of the protocols, whether it be general scalability or specific impacts from governance changes. Other participants within the blockchain community and environmental groups at large are encouraged to leverage and build upon the Framework.

2.3. Framework design

The Framework aims to quantify some of the most material environmental impacts of blockchain networks, building on existing research in the market.

2.3.1. Identifying a list of ESG impacts

The first step in the development of the Framework was to identify the material sustainability impacts that are relevant to blockchain protocols. An impact is material to blockchain protocols if it (1) is important to stakeholders (including investors, society, customers and developers) and (2) creates a significant impact on the environment, economy, and society.

Materiality impacts for ESG topics were drawn from PwC's proprietary ESG issues framework, and were supplemented by industry leading practices [13]. This list was used as a guidance for discussion and initial identification of priorities and is not exhaustive. Note that social and governance considerations, such as the access to finance, responsible product innovation, etc., are not included in the Framework.

Environment		Social	Governance
Energy use	Climate vulnerability	Access to finance	Responsible product innovation
Carbon emissions	Land and water use	Security and privacy	Risk management
Embodied carbon	Environmental policy	Community	Business ethics
Electronic waste	Energy security	Diversity, equality, and inclusion	

Table 6. Environmental, Social, and Governance (ESG) topics identified as important to blockchain networks.

2.3.2. Prioritizing material and quantifiable ESG impacts

Following a review of different blockchain protocols, current and emerging trends in the industry, and current or potential impacts blockchain protocols have on the environment, economy, and society, key ESG components were mapped according to their importance as determined by industry knowledge and experience and their feasibility of assessment.

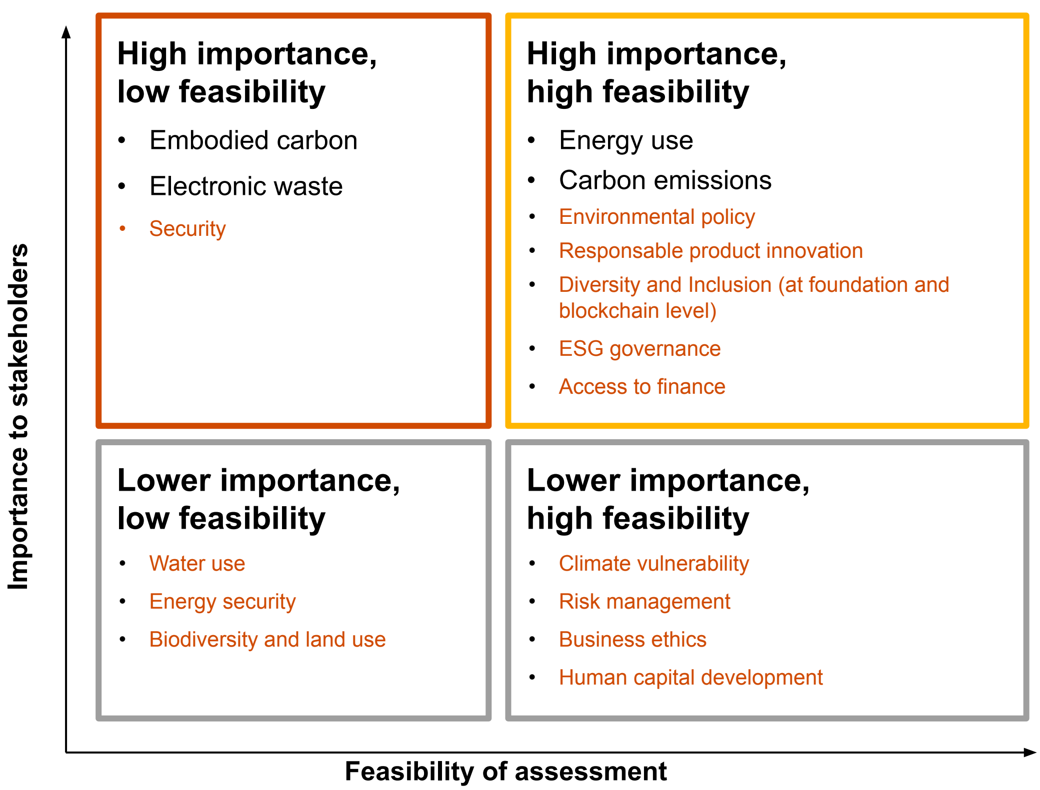
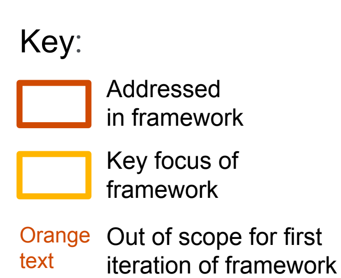


Figure 8. Matrix of stakeholder importance and assessment feasibility for each ESG topic identified.

(Note: Figure 8 illustrates examples of the different levels of importance and current feasibility of assessment)



2.3.3. Selecting environmental impacts to include in the Sustainability Framework

To balance the importance to stakeholders and feasibility, the initial version of the Framework covers a prioritized subset of three impact areas: energy use, carbon emissions, and e-waste/embodied carbon.

2.3.4. Addressing areas for further work

It is desired that future research considers the quantification of ESG impacts not included in the Framework to continue to build on the wider body of research already conducted. See Appendix 1 for a more detailed list of boundaries for analysis and potential areas for future research.

2.4. Framework overview

The Framework was designed to provide a holistic view of environmental impacts, and can be further developed in the future to include broader environmental and social impacts.

A detailed analysis of several previous environmental impact assessments of blockchain protocols found that existing assessments focus largely on energy use and its associated carbon emissions. Some studies also evaluated the embodied carbon and e-waste associated with the hardware used to participate in the consensus mechanism of a blockchain. Existing studies differ in approach, each focusing on different impact areas.

Building on the previous studies analyzed, the Framework entails four material impact areas, with between 1–2 metrics defined for each impact area.

Approach type	Impact area	Description	Metric
Quantitative approaches	**Energy use**	Energy use of the system (including the hardware running the consensus mechanism)	• Electricity use per transaction
	Greenhouse gas (GHG) emissions	Associated GHG emissions from electricity use	• GHG emissions per transaction
Qualitative approaches (with proposed metrics)	**Marginal energy use**	Energy use conducting one additional transaction	• Marginal electricity use for one additional transaction
	Embodied carbon/e-waste	Embodied carbon and end-of-life modeling of hardware used to run the protocol	• E-waste (kg) per transaction • Embodied carbon (kg) per transaction

Table 7. Approaches taken for each assessed environmental impact area.

2.4.1. Methodological limitations

The Framework attempts to further existing research and create a holistic assessment methodology; however, noting the Framework's limitations and acknowledging the difficulties of fully capturing and measuring mutually agreed upon impacts should be balanced with the perspectives presented herein. A few examples of key limitations include:

Accuracy of final results:
It may be impossible or impractical to collect information to conduct an analysis to estimate the impacts of a protocol implementation, and therefore we have exercised a level of pragmatism to judge the balance of obtaining reasonable and robust results.

Availability of input data:
The results of applying the Framework will depend on data available through the sources accessed, some of which might not be primary data and may therefore have a level of uncertainty.

Scope may be limited:
Not all ESG components were considered, and not all aspects of blockchain energy consumption were considered.

Blockchain Sustainability Framework: Deep dive into impact areas

Each of the three impact areas will be explored in detail in this section: energy use, GHG emissions from energy use, and e-waste/embodied carbon. A definition will be provided, as well as proposed metrics for measurement and accompanying rationale. The approach for measuring impact will be outlined alongside key assumptions, data sources, and boundaries.

3.1 Impact area: Energy use

3.1.1. Definition

Blockchain systems consume energy through a number of channels. The most often studied is the electricity use of the hardware used to run the relevant software, but other sources of energy consumption include data transmission networks and the energy used to manufacture the hardware used throughout the system.

Energy use also causes environmental impacts through several pathways. One of the most significant is the associated GHG emissions of energy generation. While a higher energy consumption does not perfectly correlate with higher GHG emissions[1], there remains a strong correlation, and so for the purposes of the Framework, it is asserted that a lower energy consumption leads to a smaller negative environmental impact[2]. Other secondary impacts of energy use include damage to air quality, water scarcity, and land use, but as per the earlier materiality assessment, these have not been explicitly included in the assessment.

3.1.2. Boundaries

The purpose of the Framework is to assess the impact of a blockchain protocol, thus analysis is limited to the electricity used in running the blockchain software responsible for handling transactions and electricity consumed by data transmission and storage.

The Framework does not consider upstream impacts, such as energy use in the production of validating hardware, nor does it consider the energy use of the developers creating the software.

When assessing the electricity use related to transactions, the analysis excludes the energy use of any point of sale impact, cryptocurrency wallets, applications, and "layer 2" systems[3], as these have been judged to be outside the scope of a core protocol assessment. The in-scope and out-of-scope components are illustrated in Figure 9 below.

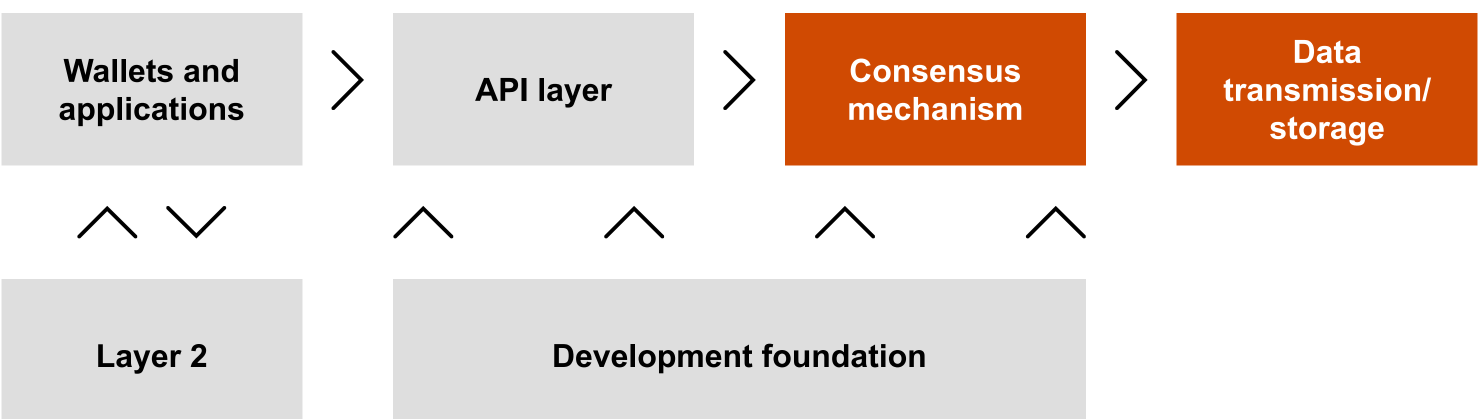


Figure 9. Simplified view of a blockchain transaction with in-scope components highlighted.

1. The GHG intensity of electricity use varies depending on the mix of fuels used to generate the electricity. It can not be assumed that all blockchain systems have similar profiles of fuels used to generate their electricity, for reasons discussed in Section 3.2.
2. The associated GHG emissions are discussed in Section 3.2.
3. Layer-2 systems are technologies that operate in conjunction with a core blockchain protocol to improve the speed, scalability and efficiency of the system. A popular example is the Lightning Network, a layer-2 system for the Bitcoin blockchain which is designed to improve transaction speeds and scalability of the network.

	Wallets and apps	Layer 2 networks	Supporting development foundation	API layer	Consensus mechanism	Data transmission /storage
Included/ not included	✗	✗	✗	✗	✓	✓
Justification	No consistent difference between blockchain and non-blockchain systems and/or limited feasibility	Not required for the ongoing operation of the layer 1 protocol	Non-profit foundations supporting the blockchain do not impact incremental energy use	No consistent application across all systems	Potential for material energy use, and sufficiently differentiated across systems	

Table 8. Justifications for inclusion/exclusion of in-scope blockchain network features.

The Framework has been developed to assess public blockchain systems and is not yet adapted for distributed ledgers or blockchains that are focused on private, permissioned use cases. The differences between blockchains are numerous, but a high-level differentiation is below:

Public vs. Private Blockchain This feature determines whether the network allows all participants to read the blockchain and initiate transactions (public blockchain), or whether the access is restricted (private blockchain).

Permissionless vs. Permissioned Blockchains: This feature determines whether network participants can take part in the proposal and validation of transactions (permissionless), or whether transaction proposal validation is restricted to a selected subset (permissioned).

It should be noted that permissioned and permissionless, restricted and unrestricted, and open and closed features may be defined differently depending on the source, and can be different across the different components of a blockchain (e.g., protocol layer vs. network layer). As such, it is important to emphasize that the explanations above are simplistic and a complete description of various blockchains architectures is outside the scope of this paper.

3.1.3. Metrics for measurement

The Framework assesses energy use of a blockchain protocol based on one primary metric.

Metric	Description	Rationale for inclusion
Electricity use per transaction	A measurement of the electricity use of one transaction, averaged out over the entire system	Transactions are one of the most common use cases for blockchain. Measurement of this foundational use case enables assessment of more complex blockchain use cases which utilize multiple transactions

Examining the case for attributing energy usage to transactions: dynamics of a blockchain transaction and its contribution to energy consumption

How is a transaction added to the ledger?

The first step in adding a transaction to a distributed ledger is through a user broadcast of a transaction to nodes on the network. Validating or block-proposing nodes typically store the transaction information in a "mempool", a waiting area for unconfirmed transactions. Block-proposing nodes then batch individual transactions together for inclusion in the next block in the blockchain. A set of validation checks are conducted, such as verifying that the wallet holds sufficient funds to complete the transaction. The consensus mechanism (e.g., proof-of-work, proof-of-stake, Federated Byzantine Agreement, etc.) is then applied to validate the block of transactions.

Different network participants can attempt to validate different transactions; there is no guarantee that any individual transaction will be included in a block, as the space in a block is limited. Indeed, it is not a strict requirement on many blockchains that any transactions are included, and it is theoretically possible to add a block to the blockchain devoid of any transactions.

However, fees are often paid to block proposers to incentivize the proposer to include a specific transaction on the blockchain. This fee amount can often be modified by the transacting party to provide greater incentive to include their transactions over competing transactions.

How might network participants be incentivized to validate transactions?

Networks incentivize participation in block validation through a variety of methods. First, some networks incentivize validators/miners through distribution of a transaction fee paid by the user creating the transaction. To further incentivize validators/miners to include a transaction on the ledger, which is occasionally not guaranteed due to a limited amount of space in a block, the transaction fee can be adjusted upward beyond the minimum required fee.

In proof-of-stake blockchains, validators may earn some of the network's native token by validating a block proposed by another validator. Further, "delegators" may also earn rewards by staking their tokens with a staking pool. The staking pool then shares with the delegators a proportionate amount of their delegated stake in return for assisting in consensus. This effectively distributes the validation power to more users than those who simply have a validating node and a significant amount of resources, thus increasing decentralization and network security.

One incentive worth noting is that of "slashing". In some networks, validators who participate in network consensus must "stake" some amount of token to participate in consensus. If the validator acts maliciously, makes mistakes, or falls offline it can have its staked token slashed, meaning that they lose those tokens.

Not all blockchains reward miners/validators—as demonstrated by some Federated Byzantine Agreement (FBA) blockchain protocols, some networks do not provide direct financial rewards to participate in validation; rather, the incentive is based on the ability to participate in the network to improve its security and to help decide the future of the network.

Do additional transactions lead to additional electricity usage?

As miners and validators could technically choose to not include any transactions in a block, electricity could be consumed without validating any transactions. For consensus mechanisms that offer a financial reward, the electricity use could be therefore equated to the primary financial reward in the form of currency that validators/miners receive when they validate/mine a block. However, for protocols where miners and validators receive a financial reward when transactions are included in ledgers they mine/validate, the aforementioned argument can be countered as it is economically sensible to include transactions. This methodology thus assumes that the electricity use per transaction is a valuable metric to compare electricity use of different blockchain networks as there are financial incentives to include transactions on ledgers. The assumption is further based on the understanding that additional transactions can lead to additional electricity usage as more blocks have to be validated/mined, thus marginally increasing the overall electricity consumption. If a network does not offer any monetary reward, there is no incentive to validate empty blocks in the first place.

In cases where financial rewards are not provided in return for mining a currency—such as in Stellar or Ripple—marginal increases in electricity use are potentially less feasible to predict. Nodes on these networks are motivated by non-financial rewards such as the ability to directly support the security and health of the network. Further, in many cases, validators may benefit from “issuer enforced finality” [15] , a dedicated pipeline for submitting transactions, and unlimited access to data reads from the blockchain. Given the above, the number of validator nodes may not be correlated with the underlying asset price.

How is the metric electricity use per transaction calculated?

Total electricity use over a certain period of time is measured and divided by the number of transactions that were executed on the blockchain during this specific time frame.

3.1.4. Approach to measurement

Due to the decentralized nature of blockchain systems and the vast number of pseudonymous participants, it is not practically feasible to retrieve electricity usage data for each participant for permissionless systems. Defined below is a set of approaches to estimating the overall electricity use of a blockchain ecosystem, from which one can infer results for each of the metrics.

A number of potential approaches exist to estimate the electricity use of a blockchain ecosystem, each with different data requirements, assumptions, and levels of robustness [16]. The validity of these assumptions varies between consensus mechanisms, and as such no single approach provides a high degree of robustness in measuring possible blockchain protocols. For this reason, the Framework defines two primary approaches, each aligned to a set of consensus mechanisms. The comparability of results from a mixed-method approach is discussed below.

For proof-of-work (PoW) systems, an economic approach is used to estimate a lower and upper bound of electricity use. The latest calculation methodology from the Cambridge Bitcoin Electricity Consumption Index is adapted and used to assess electricity consumption of these PoW blockchains [1]. For blockchain protocols deploying any other consensus mechanism such as proof-of-stake (PoS), Federated Byzantine Agreement (FBA), or other non-PoW approaches to consensus, direct electricity measurement of a reference piece of hardware is used to extrapolate the electricity consumption of the entire network. If direct energy measurements are not available, lower bound estimates can be made using an approach based on the minimum reference hardware requirements of the system.

	PoW consensus mechanisms	Non-PoW consensus mechanisms	
Preferred approach for estimating energy use	Economic estimates of energy use	Direct energy measurement of a reference piece of hardware	Estimated energy consumption (lower bound)
Description of approach	Approximates electricity costs based on the value of mining revenue. Based on an assumption that individual miners are economically rational actors	Assesses electricity use at the level of specific hardware components (e.g., CPU, memory, network, etc.) and extrapolates this data for the entire network	Multiply the number of active nodes (PoS/FBA) with electricity use of a piece of hardware that satisfies the minimum hardware requirements

Table 9. Preferred energy calculation approaches for blockchain protocols by consensus type.

(Note: For non-PoW consensus mechanisms, the direct energy measurement approach was preferred for the quantitative analysis, with the lower bound estimate approach addressed qualitatively.)

Although defining multiple approaches impacts the comparability of the results which may be generated by applying the Framework, this is justified based on **a priori** assumptions. PoW-based protocols generally employ different incentivisation mechanisms and/or require different system hardware than PoS, FBA, and protocols with other non-PoW consensus mechanisms.

Proof-of-work (PoW)

PoW blockchain protocols rely on the process of mining, the act of solving cryptographic hash puzzles to verify blocks of transactions. Mining is often performed by computing systems with circuit chips that have been optimized for solving the hash puzzles of a given protocol. The miner that correctly guesses the block's hash gets a reward in the form of the native cryptocurrency.

Mining hardware differs for each PoW consensus protocol, but at its core, mining consists of expending electricity in the form of work (unit of Joules, J) to compute hashes (h). Hashrate (H) is the term for the number of hashes being computed on a network per unit of time, and can be estimated from the number of blocks being mined and the current block difficulty.

In making an economic estimate for electricity use of a PoW protocol, the key underlying assumption is that miners are rational economic actors who will only continue the act of mining if it remains profitable. This notion results in the following inequality [1]:

$$v \times p_{El} \leq R$$

Where v = mining hardware efficiency (J/h)

p_{El} = electricity cost (USD/J)

R = mining revenue per hash (USD/h)

According to this equation, miners only run their equipment when the mining revenue per hash outweighs the electricity cost per hash. This inequality does not take into account other capital or operational expenses incurred by miners.

In order to calculate an estimate for the efficiency of mining hardware (Jh), one can observe the power consumption of mining hardware (unit of Watts, W) and divide by the network's hashrate. Miner revenue is variable based on the state of the network at a given time but can be approximated by averaging the hashrate and fees paid out to miners against the price of the cryptocurrency over a period of time.

Thus, gathering a profitability threshold for miners, the previous equation can be reworked as [1]:

$$v_{critical} = \frac{R}{p_{El}}$$

Where $v_{critical}$ = profitability threshold of hardware efficiency (J/h)

One can estimate the upper limit of total yearly electricity consumption by assuming that we're using the least electricity efficient yet still profitable hardware as well as using a high power usage effectiveness (PUE) as reported by miners. One can then multiply by blockchain hashrate (H), or total computational power that is being used to mine and process transactions per second. This results in the following mathematical expression [1]:

$$E_{UL} = v_{critical} \times PUE_{UL} \times H \times (60\frac{sec}{min}) \times (60\frac{min}{hr}) \times (24\frac{hr}{day}) \times (365.25\frac{day}{yr})$$

Where E_{UL} = upper limit yearly power consumption (W)

$v_{critical}$ = energy efficiency of least efficient yet still profitable hardware (Jh)

PUE_{UL} = upper limit power usage effectiveness

H = hashrate (h/sec)

Using a similar method, an estimate can be constructed for the lower bound total yearly electricity consumption by the following expression [1]:

$$E_{LL} = v_{LL} \times H \times PUE_{LL} \times (60\frac{sec}{min}) \times (60\frac{min}{hr}) \times (24\frac{hr}{day}) \times (365.25\frac{day}{yr})$$

Where E_{LL} = lower limit yearly power consumption (W)

v_{LL} = energy efficiency of most efficient hardware (J/h)

PUE_{LL} = lower limit power usage effectiveness

H = hashrate (h/sec)

This lower bound expression acts under the assumptions that miners will run the more efficient hardware available, while maintaining mining facilities with little-to-no overhead.

Assumptions

The proxy generated by this methodology is sufficient to get an understanding of the upper and lower bounds of electricity consumption as PoW's electricity consumption is several times higher than PoS/FBA

The global average electricity price for mining is constant between $0.05 and $0.10 per kWh. This number is consistent with estimates used in past research [1]. Differences in assumed electricity prices between PoW blockchains is due to the fact that some run "ASIC-resistant" PoW algorithms. ASICs have led to the industrialization of mining through dedicated mining farms that seek locations with low-cost electricity, while some PoW-based protocols give preference to GPUs that can be found in home computers

During time periods where mining equipment is not profitable, the model uses the time of the last known profitable equipment

For calculation of the lower bound of electricity consumption, it is assumed that miners always use the most efficient hardware available. It is also assumed that all mining facilities in the lower bound estimate have a PUE (power usage effectiveness) of 1.02 [16]. Note that this is substantially below reported PUE figures for hyperscalers, and as such may represent a generous lower bound

For calculation of the upper bound of electricity consumption, the assumption is miners use the least efficient hardware available at that time as long as it is profitable. It is also assumed that all mining facilities in the upper bound estimate have a worst-case PUE of 1.25 to remain profitable [16]

Other consensus mechanisms (including proof-of-stake (PoS) and Federated Byzantine Agreement (FBA)

This methodology employs two different calculation approaches to assessing electricity consumption. The first approach assumes that the systems used to run blockchain protocols are broadly similar in the distribution of hardware and can therefore be assessed using a common methodology. This does not imply, however, that hardware requirements should be identical between protocols. As such, direct energy calculations and estimates take into account build specifications and utilization. The second approach aims to estimate the lower bound of electricity use based on the minimum hardware requirements to run a given protocol, a method that allows for estimation where direct measurements are not available. These methodologies aim to estimate the electricity use per node or a subset of nodes, which is then extrapolated to the total number of nodes in the network to calculate the total electricity consumption.

Direct energy measurements of a reference piece of hardware

The first approach to assessing the electricity consumption of non-PoW consensus mechanisms is based on the measured electricity use of validating nodes and other node types that are critical for the ongoing operation of the protocol. Infrastructure measurements are attained by setting up a node and participating in consensus or obtaining data outputs from an active validator node or set of nodes. Electricity use of CPU, RAM, storage, and network are then measured from the active node(s).

Electricity use of CPU, RAM, and storage are determined by observing time series infrastructure measurements of the server on which the node is set up, converting infrastructure data to electricity using coefficients, and multiplying the sum of the server components by the power usage effectiveness (PUE) of the data center. The network electricity consumption is determined based on the incoming and outgoing network traffic in bytes for each server and multiplied with a coefficient to assess the electricity consumption. This results in the following equation:

$$E = (CPU + RAM * \alpha + S * \beta)\ PUE + N * \gamma$$

Where E = total electricity consumption (Wh)

CPU = electricity consumption of the central processing unit (Wh)

RAM = electricity consumption of memory (GB)

α = coefficient to estimate electricity consumption of RAM (GB)

S = amount of data stored (GB)

β = coefficient to estimate electricity consumption based on storage needed (Wh/GB)

PUE = power usage effectiveness if applicable, if not = 1

N = network data transmission, incoming and outgoing (GB)

γ = coefficient to estimate electricity consumption based on data transmission (Wh/GB)

Ongoing CPU wattage of systems may be made available directly by running average power limit (RAPL) interfaces, however not all platforms offer this capability. If an RAPL interface is not present, an estimate of the electricity consumption of the CPU can be made as a function of minimum and maximum wattage and average CPU utilization.

$$CPU = Minimum\ wattage + Average\ CPU\ Utilization * (Maximum\ wattage - Minimum\ wattage)$$

Minimum hardware requirements

To assess the lower bound of electricity consumption for different hardware protocols, the minimum hardware requirements for each protocol may be assessed and cross-referenced with manufacturer data for each device. The hardware is assumed to run at 100% CPU usage as it does not exceed the minimum hardware requirements. Therefore, the respective manufacturer-provided electricity consumption data can be used to compare the lower bound electricity use of different protocols.

To assess the electricity use from network and storage, this methodology proposes three different options.

Option 1 holds the assumption that storage and network electricity usage does not vary or is immaterial across different protocols and is omitted in this part.

Option 2 is to use the storage and network electricity usage that is taken from the reference piece of hardware.

Option 3 assumes that the minimum requirements for storage for each individual protocol can be used and multiplied with a coefficient to receive the minimum electricity consumption for storage, and use either Option 1 or 2 for network electricity consumption.

Using a combined approach of **Options 1** and **2** leads to a mathematical expression in the following form:

$$E = (C + S * \beta)\, PUE + N * \gamma$$

C = manufacturer-provided data on electricity consumption of piece of hardware (Wh)

S = amount of data stored (GB)

β = coefficient to estimate electricity consumption based on storage needed (Wh/GB)

PUE = power usage effectiveness if applicable, if not = 1

N = network data transmission, incoming and outgoing (GB)

γ = coefficient to estimate electricity consumption based on data transmission (Wh/GB)

Assumptions

The Framework assumes that non-PoW protocols are broadly similar in the distribution of hardware and can therefore be assessed using a common approach. This does not imply, however, that hardware requirements are identical between protocols. Hardware specifications must be considered whether for estimating electricity consumption of a reference piece of hardware or minimum hardware required.

The distribution of hardware in non-PoW systems is assumed to be negligible, i.e., by using a reference piece of hardware the total electricity consumption of the network can be approximated and divided by the number of transactions.

A previous survey [2] found that the assumption of hardware similarity held true for Stellar nodes, with only one of 24 surveyed nodes self-hosted on a home device, and the remainder run on servers run by dedicated hosting providers. A separate study [17] found a significant proportion of 'baking nodes' were run on home hardware. Although the study indicates that assuming identical hardware between protocols may not be valid, it is nonetheless useful to employ the aforementioned assumption because the hardware requirements remain to be similar. To expand upon this topic, the Framework aims to provide a current-state snapshot of impact and compare the fundamental differences in impact across protocols. By comparing a common reference point, the Framework draws meaningful conclusions on comparative impact. It is conceivable that future hardware distribution across protocol ecosystems will continue to converge.

The coefficient for network data transmission, γ ,is an estimate of the average electricity intensity of transmitting data through the Internet and does not separately consider the electricity used by routers and switches to facilitate data transfer.

Coefficients

The coefficient α, relating RAM to electricity use, is 0.392 Wh/GB [18]

The coefficient β, relating data storage to electricity use, is 1,200 Wh/GB [18]

The average PUE of data centers is 1.125 [18]

The coefficient γ, relating data transmission to electricity use, is 0.023 kWh/GB [19]

In the most efficient case, taking into account only the data exchanged between different geographical data centers within the same company, this coefficient may be closer to 0.001 kWh/GB [18]

When estimating the electricity consumption of the CPU without RAPL or access to wattage figures, minimum wattage (at 0% utilization) can be estimated as 0.74 Watts and maximum wattage (at 100% utilization) can be estimated as 3.84 Watts

3.1.5. Data sources

Proof-of-Work (PoW)

Parameter		Description	Unit	Data source
Electricity cost	p_{El}	Estimated average cost of electricity across all miners	$\frac{USD}{kWh}$	CBECI
Miner revenue per hash	R	Mean miner reward per estimated hash unit performed	$\frac{USD}{h}$	Sources will vary based on protocol

Proof-of-Work (PoW)

Hashrate	H	Average rate at which miners are solving hash puzzles	$\frac{Th}{s}$	Sources will vary based on protocol
Mining equipment efficiency	v	Measurement of electricity efficiency of a given mining hardware type	$\frac{J}{Gh}$	Sources will vary based on protocol
Power usage efficiency	PUE	Measurement of data center energy efficiency	-	Cloud Carbon Footprint
Transactions per day	t	Number of daily network transactions	$\frac{txn}{day}$	Sources will vary based on protocol

Table 10. Parameters, descriptions, and data sources for PoW electricity use calculations.

Proof-of-Stake (PoS) and Federated Byzantine Agreement (FBA)

Parameter		Description	Unit	Data source
CPU	CPU	Electricity consumption of CPU	kWh	Measured
RAM	RAM	Memory usage per node	$Byte$	Measured
Coefficient for RAM	α	Coefficient for electricity used per gigabyte of RAM	$\frac{kWh}{GB}$	Cloud Carbon Footprint
Storage	S	Storage usage per node	$Byte$	Measured
Coefficient β for storage	β	Coefficient for electricity used per terabyte of storage	$\frac{kWh}{TB}$	Cloud Carbon Footprint
Power usage efficiency	PUE	Power usage efficiency	-	Cloud Carbon Footprint
Network traffic	N	Network traffic, incoming and outgoing from node (converted from bits per second)	$Byte$	Measured
Coefficient for network traffic	γ	Coefficient for electricity used per min or byte of network traffic	$\frac{kWh}{GB}$	Aslan et al

Table 11. Parameters, descriptions, and data sources for PoS and FBA electricity use calculations.

3.2 Impact area: Greenhouse Gas (GHG) emissions from electricity use

3.2.1. Definition

As noted previously, the electricity use of blockchain systems results in GHG emissions, which contribute to global warming. The volume of GHG emissions produced depends on both the volume of electricity used as well as the emissions intensity of the electricity used to power the system.

3.2.2. Boundaries

The Framework applies the same boundaries as those defined in the energy use impact section.

3.2.3. Metrics for measurement

The Framework assesses the GHG emissions of different blockchain protocols based on results of energy use impact assessment, and therefore defines linked metrics.

Metric	Description	Rationale for inclusion
GHG emissions per transaction	A measurement of the GHG emissions produced by one transaction.	Transactions are one of the most common use cases for blockchain. Measurement of this foundational use case also enables assessment of more complex blockchain use cases which utilize multiple transactions.[1]

Proof-of-work (PoW)

For PoW blockchains, GHG emissions are calculated using the distribution of hashing power or the node distribution of the network. Hashing power is expected to be a better representation of where energy is being used; however, reliable data is not always available. As such, the geographic distribution of nodes is used as a proxy for the approximate geographic distribution of energy consumption across the network.

The percentage of the hashing power/node distribution per country is then multiplied by the percentage of non-renewable resources used in each participating country. As such, the resulting GHG emissions for each PoW platform is the energy consumption of that platform reduced by the renewable energy consumption used by that platform.

3.2.4. Approach to measurement

To estimate the emissions associated with electricity use, the Framework defines an approach to first estimating the emissions intensity of the energy used to power the system. This approach varies by consensus mechanism. The Framework therefore cannot assume a single global emissions intensity of electricity, or even rely on national level estimates.

Instead, the Framework draws on third-party survey data, which provides self-reported information on the energy mix used by PoW miners. This approach is not without limitations, however. The two most prominent are the difficulty in assessing the quality of self-reported data, and the timeliness of data. The latter is particularly important, as the policy landscape for PoW mining has shifted rapidly in recent years, which is likely to have dramatically shifted mining locations and energy mix utilized. It is hoped that through initiatives such as the Crypto Climate Accord [20], the coverage, quality, and timeliness of data on the emission intensity of the electricity used for PoW mining will likely increase with time.

1. Some blockchain protocols define a set of even more foundational operations. However, to allow for comparability with protocols that lack similar operations, the Framework elects to assess electricity use at the transaction level.

To calculate the emissions of PoW mining, the following approach is taken:

$$T = \sum_{C}(E_C \times I_{C,\,G-R} \times (100\% - M_{C,R}))$$

Where T = total emissions (kg CO_2e)

C = set of countries where mining occurs

E_C = protocol electricity generation in country "C"

$I_{C,\,G-R}$ = emissions intensity of the local grid in country C, excluding renewables (kg CO_2e/kWh)

$M_{C,R}$ = share of electricity used in country C for cryptocurrency mining sourced from renewables

*Upper and lower-bound estimates for emissions are calculated through different approaches to estimating regional share of renewables, as detailed in the data sources section below.

Assumptions

For the proportion of electricity that is not directly sourced from renewables, it is assumed an emissions intensity in line with the local grid (less contribution from renewable sources). This potentially underestimates the contribution to emissions from more emissions-intensive dedicated power plants.

The Framework assumes that the regional share of hashing power is consistent across PoW systems.

Other consensus mechanisms (including proof-of-stake (PoS) and Federated Byzantine Agreement (FBA))

In contrast to PoW systems, which incentivize the use of specialized mining hardware, the majority of blockchain protocols that employ alternative consensus mechanisms can be run on general purpose hardware. Survey data suggests that participants in the system often run the protocol's software on enterprise cloud servers [2].

An emissions estimate for the operation of non-PoW protocols can be calculated using an adapted version of the previous mathematical expression as such:

$$T = \sum_{C}(E_C \times I_{C,\,D})$$

Where T = total emissions (kg CO_2e)

C = set of countries running participating nodes

E_C = protocol electricity generation in country "C"

$I_{C,\,D}$ = cloud grid emissions intensity in country C (kg CO_2e/kWh)

Assumptions

It is assumed that data centers that make use of renewable energy credits (RECs) can be treated as having that proportion of their electricity attributed to renewable sources. In practice, electricity for such data centers is often drawn directly from the grid, which includes a mixture of low-carbon and carbon-intensive energy sources. There is a growing trend amongst technology companies to go a step further and achieve so-called “24/7 carbon free energy”.

The Framework assumes that blockchain protocols run on servers with identical GHG electricity intensity. In practice, a scan of validator node IP addresses reveals differences in the mix of cloud providers being utilized across blockchain protocols. However, many of these ecosystems are still in their early stages, and might expect such differences to diminish over time as the networks mature and the number of participants increases. It is therefore more meaningful to examine the comparative impact of blockchain protocols on identical assumptions, rather than narrowly focusing on a more granular but time-limited current state assessment.

Likewise, the Framework assumes that the software is being run on the infrastructure of major cloud providers, rather than smaller cloud providers or local servers, which may have higher GHG intensities of electricity. Previous survey data finds that this assumption is largely correct, but may skew overall results slightly down [2].

The methodology uses the cloud grid intensity based upon data from several large cloud providers. Emissions intensity is based on six large regions including North America, South America, Africa, Asia Pacific, the European Union, and the Middle East. Geographic node distribution is determined using publicly available data and multiplied proportionally by the average cloud grid intensity for each respective region. For blockchain protocols that do not have reliable data regarding the geographic distribution of nodes, an average of the blockchains which do have available data may be used as a proxy.

What are Renewable Energy Credits?

Renewable Energy Credits (RECs) (also known as Renewable Energy Certificates) are tradable credits that certify that the owner has bought a certain amount of renewable electricity.

RECs are created when renewable electricity is injected into the grid and serve as a measure to identify the total amount of renewable electricity in the grid, as renewable electricity is non-distinguishable from non-renewable electricity once in the grid. The consumer's electricity is usually a mix of renewable and non-renewable electricity as it is from the grid. For each MWh of renewable electricity injected into the grid, the producer generates an equivalent amount of RECs. These RECs are sold to the consumer to certify that an equivalent amount of the consumed electricity is from renewable sources.

How do renewable energy credits differ from carbon credits?

Carbon credits are certificates purchased that certify that a certain amount of emitted carbon emissions have been canceled out by a reduction of carbon emissions in a different context. These projects reduce, remove, or avoid greenhouse gas emissions and can also bring a host of positive co-benefits such as empowering communities, protecting ecosystems, restoring forests, or reducing reliance on fossil fuels. While carbon credits play an important role in being able to achieve net zero emissions, the leading practice is that the first-line solution for emitters should be to decrease emissions as much as possible, and only offset the emissions that are unavoidable.

3.2.5. Data Sources

Proof-of-Work (PoW)

Parameter		Description	Unit	Data source
Regional share of hashing power (%)	C, E_C	Percentage distribution of nodes (hashing power in the case of Bitcoin) globally	-	Sources will vary based on protocol
Emissions intensity (excluding renewables)	$I_{C,G-R}$	Country emissions intensity used to convert electricity to emissions	$\frac{kg\ CO2e}{kWh}$	Sources will vary based on protocol node distribution
Mining sourced from renewables (%)	$M_{C,R}$	Estimated percentage share of electricity used for mining that has been sourced through renewables	-	CCAF

Table 12. Parameters, descriptions, and data sources for PoW GHG emissions calculations.

Proof-of-Stake (PoS) and Federated Byzantine Agreement (FBA)

Parameter		Description	Unit	Data source
Geographic distribution of nodes	C, E_C	Provides the overall distribution of the nodes across different countries for different blockchains	-	Sources will vary based on protocol
Carbon intensity of cloud providers	$I_{C,D}$	Consists of data on grid emission intensity country-wise for three cloud service providers The data is aggregated into regions for using in the GHG emission estimations	$\frac{kg\ CO2e}{kWh}$	Cloud Carbon Footprint

Table 13. Parameters, descriptions, and data sources for PoS/FBA GHG emissions calculations.

3.3 Impact area: e-waste/embodied carbon

3.3.1. Definition

This section focuses on estimating the environmental impact of hardware from two angles. First, the Framework provides the methodology to suggest how you could estimate the volume of e-waste produced by a blockchain protocol.

What is e-waste?

E-waste refers to electronic and electrical equipment that has been discarded. According to the European Union (EU), it is the fastest growing waste stream in the EU, and less than 40% of it is recycled [21].

Increased generation of e-waste generates negative environmental and social impacts through a number of channels, including:

- Biodiversity impacts and water pollution through greater demand for mining of raw materials.
- Human rights impacts, through potential disturbances of land belonging to racially/ethnically diverse populations for new mines, and accusations of labor issues in mining.
- As the world decarbonizes, it is expected society will transition from a fuel-based economy to metals and minerals-based economy. E-waste contributes to resource scarcity in this regard and continues to be hampered by low levels of recycling. For example, research suggests that there is 100 times more gold in a tonne of e-waste than in a tonne of gold ore [22], but less than 20% of e-waste is recycled.

As e-waste refers to a broad category of waste, it should be noted that not all e-waste generates the same impacts on the environment and on human health. While this somewhat limits the validity of direct comparisons between the volume of e-waste generated by blockchain applications and that generated through other sources, it is nonetheless true that blockchain-related e-waste leads to negative environmental impacts, and efforts should therefore be made to reduce e-waste.

Second, the Framework provides the methodology to suggest how the embodied carbon of the hardware associated with running a protocol could be estimated.

What is embodied carbon?

Embodied carbon refers to the total GHG emissions generated in producing a piece of physical hardware. This covers emissions associated with the extraction of raw materials, the manufacturing of the asset, and the transport to the customer. Some assessments of embodied carbon also cover the carbon associated with the end-of-life processes of disposing of the hardware (e.g., incineration or recycling).

These impacts can be significant. For example, research suggests that a typical smartphone requires 6.5kg of mined ore to produce the 75g of metal contained within and that the production processes emit around 60kg of CO_2e, over 300 times the weight of the phone [23]. For many pieces of IT equipment, the emissions generated during manufacturing can be greater than those arising from their use.

3.3.2. Boundaries

This methodology focuses exclusively on the impact of hardware used to participate in the consensus mechanisms (e.g., servers, laptops), but excludes hardware associated with internet access equipment (e.g., routers).

3.3.3. Metrics for measurement

Metric	Description
E-Waste (kg) per transaction	A measurement of the e-waste associated with the hardware required by one transaction. Takes into account the frequency the hardware is renewed.
Embodied carbon (kg) per transaction	A measurement of the embodied carbon associated with the hardware required by one transaction. Takes into account the frequency the hardware is renewed.

3.3.4. Approach to measurement

For both metrics, estimates can be generated of the hardware used in running the blockchain protocol and its lifetime. For e-waste, the total amount of e-waste generated is considered and would include any considerations of recycling. To assess embodied carbon, life-cycle assessments of the different types of hardware can be generated and multiplied with their respective distribution in the different protocols (see approach below for different consensus mechanisms).

To compare across protocols, the total volume of e-waste and embodied carbon can be divided by the total amount of transactions over the relevant data collection period. This aspect of analysis was not performed as part of this study.

Incentives driving differing electronic hardware makeup across consensus protocols?

How are transactions validated on proof-of-work (PoW) protocols?

PoW protocols require participants in the network to provide evidence that they have expended a defined amount of computational power by solving a cryptographic hash problem.

These problems are often designed to have several key features, including:

Asymmetry in the difficulty of solving a solution versus validating an answer: The mathematical problems defined by PoW protocols are known to require large amounts of effort to solve, but solutions can be validated with minimal effort. This means that a solution put forward by a particular miner can be easily validated by other participants in the network, effectively confirming that the miner in question has expended the requisite amount of computational effort.

Requires trial and error to solve: Miners must repeatedly perform the same set of functions, varying the input each time until the desired output is reached. Critically, it is not possible to predict what inputs might produce a particular output.

In practice, this is often achieved by requiring miners to use as inputs a set of transactions that have yet to be validated, combined with a "nonce" (a randomly number selected by the miner) and apply a cryptographic hash function to produce an output with specific properties defined by the protocol. Participants in the network race to find a nonce that may produce the desired output, and be the first to validate the block of transactions.

How do the incentives for validation in PoW systems affect hardware makeup and environmental impact?

Participants in PoW systems can be incentivized by profit motives to use "efficient" hardware, measured by two factors:

High computational/hashing power, which increases the likelihood the participant will be the first to validate a block of transactions and therefore receive the associated economic rewards.

Low costs, including capex (the cost to purchase the hardware) and opex (the cost to run the hardware, typically dominated by electricity costs).

This has resulted in a trend over recent years of participants disfavoring general purpose hardware and shifting towards specialized hardware tailored to the cryptographic mathematical problems required to mine on specific blockchain protocols. This has led to a rise in the use of ASIC miners (application-specific integrated circuits), which can provide the greatest dollar-to-hashing power ratio for many PoW protocols.

However, ASIC miners cannot easily be repurposed for other use cases. In addition, increases in the efficiency of new generations of hardware can incentivize miners to upgrade their hardware regularly, in order to maintain a sufficiently high hashing-efficiency so as to remain profitable. This means that the hardware used for mining is often discarded more quickly than general purpose hardware, with estimates of volumes of e-waste discussed later in this section. This continual race to the top also has a knock-on effect on levels of decentralization and security, as it can lead to ecosystems where mining power is concentrated in the hands of a smaller number of large actors with the financial power to invest in such upgrades.

It should be noted that not every PoW protocol incentivizes a shift towards specialized hardware. The blockchain protocol Monero, for example, is described as an "ASIC-resistant cryptocurrency", as its consensus mechanism is claimed to have been designed and regularly updated to offer no benefit for ASIC miners over general-purpose and consumer-grade hardware. Others, such as Ethereum, have also focused on remaining ASIC-resistant. ASIC-resistant protocols, therefore, incentivize greater use of general-purpose hardware than non-ASIC-resistant protocols.

How does this compare to other consensus mechanisms, such as proof-of-stake and Federated Byzantine Agreement?

Other consensus mechanisms do not rely on large volumes of computational effort to achieve security. Participants in the network typically have no economic incentive to operate hardware that exceeds the minimum system requirements of the protocol, leading to greater proportional use of consumer hardware (such as desktop computers, laptops, or phones) and cloud computing for validation.

Proof-of-Work (non-ASIC-resistant protocols)

The first step in the Framework's methodology is to conduct a high-level qualitative assessment of whether the given blockchain protocol is ASIC-resistant, based on published academic and gray literature.

For protocols that are not ASIC-resistant, it is assumed that materially the hashing power of the network derives from ASIC miners. Previous attempts to estimate the volume of e-waste associated with PoW protocols have taken a variety of approaches, which are detailed in the literature review section of this report. Given the lack of available data and the uncertainty in estimates, the Framework proposes several approaches to estimating average lifetime, providing lower—and upper—bound estimates.

Approaches to estimating average lifetime of an ASIC miner

Approach	Description
Estimates based on total hardware production	By taking estimates of total ASIC production, one can calculate implied hashing power and compare this to the observed hashing power of the network. Building on the assumptions in earlier sections on the current makeup of the network, one can estimate what volume of ASIC miners are no longer in use.
Estimates based on mainstream Bitcoin mining hardware	In general, it is not possible to accurately estimate the hardware makeup of a blockchain network without survey data. However, for specific mining hardware, one can track the reduction in hashing power contributed by this type of hardware and can estimate the rate at which ASIC mining hardware is discarded. It can then be asserted that this discard rate can be applied to other ASIC miners.
Estimates based on published depreciation schedules	A substantial proportion of mining is conducted by registered businesses dedicated to mining. Several of these businesses publish financial statements, which include depreciation schedules for their assets (including mining hardware), which is averaged to produce hardware lifetime estimates. Depreciation schedules can vary based on the hardware used and the time period evaluated. As accounting practices in the blockchain sector mature and converge, it is hoped that future applications of the Framework will be able to rely on a narrower and increasingly consistent set of data.
Estimates based on profitability of hardware	Building on the methodology in the energy use section of the Framework, it is estimated the point in time at which different popular ASIC miners became unprofitable, based on average economic rewards from mining and assumptions on electricity prices. It is assumed that hardware is discarded when it becomes unprofitable, and compares these to the launch data to estimate lifetime. Finally, the results were averaged for a selection of popular mining hardware to produce an estimate of the average useful life.
Estimates based on Koomey's law	Koomey's law describes a trend in the increase in the energy efficiency of computing hardware with time. It is asserted that mining hardware is discarded and replaced with newer versions as often as efficiency doubles.

Table 15. Approaches for estimating the average lifetime of an ASIC miner.

Assumptions

Estimates based on total hardware production

It is assumed that one can obtain reliable data regarding the hashing power of the network.

It is assumed that miners are rational actors who discard ASIC miners when it is no longer profitable to use them.

Estimates based on mainstream Bitcoin miner activity

It is assumed that the observed irregularity in the distribution of nonces is attributable to the mining hardware, as per Coin Metric analysis [24].

It is assumed that the average lifetime of the evaluated mainstream mining hardware can be applied to ASIC miners.

Estimates based on published depreciation schedules:

It is assumed that the discarding of hardware follows depreciation schedules. As depreciation schedules are forward-looking, there can be uncertainties in external factors (such as the profitable lifetime of the hardware, or the availability of replacement hardware) may impact the rate at which hardware is discarded in reality. This is partially reflected in the wide range of depreciation schedules observed.

Estimates based on the profitability of hardware

When calculating the lifetime of a piece of hardware, it is assumed that the hardware is bought in the year the hardware was launched and is discarded when it becomes unprofitable.

It is assumed that estimates of lifetimes for a selection of ASIC miners can be applied to hardware as a whole.

As with earlier sections, a global electricity price is used. In practice, some miners will have access to lower-priced electricity than others. This may result in hardware that is unprofitable at “grid prices” being sold to mining farm operators who can operate the hardware profitably through cheaper electricity.

Estimates based on Koomey’s law:

Mining hardware is discarded as often as Koomey’s hardware finds the efficiency of hardware doubles (i.e., every 2.6 years).

Proof-of-Work (PoW) (ASIC-resistant protocols)

For protocols which are ASIC-resistant, the Framework applies estimates from literature on the lifetime of consumer mining hardware (e.g., graphics cards) when utilized at a high intensity. The Framework also takes into account estimates of the proportion of the hardware's utilization that is deployed towards mining.

As is the case for cryptocurrencies that utilize ASICs for mining, it is likely that rational actors will gravitate to configurations which are best suited economically for the mining of ASIC-resistant PoW protocols. Therefore, approaches used to estimate the hardware used in the above section can also be applied to ASIC-resistant protocols. It should be noted that many different types of computers can and are used for ASIC-resistant protocols; as such, the calculations will likely not be as simple or accurate when extrapolated to a large number of miners.

Other consensus mechanisms (including proof-of-stake (PoS) and Federated Byzantine Agreement (FBA))

Non-PoW blockchains that rely on other consensus mechanisms, such as PoS and FBA, do not typically create incentives for utilizing hardware that exceeds minimum requirements, and are often run on consumer hardware or cloud computing servers. However, distribution of hardware type nonetheless varies depending on the individual blockchain network under examination. For example, a survey conducted on bakers and validators revealed that a broad mix of personal laptops, single-board computers, and cloud servers were used [17]. On the other hand, 96% of all survey participants of a survey conducted by Stellar Development Foundation of Stellar node operators ran their nodes in a cloud environment [2].

The volume of e-waste and associated embodied carbon impact varies by hardware type and how it is operated and disposed of. It is recognized that detailed data on the hardware makeup and operations of every blockchain protocol is not readily available. To manage this data gap while allowing for consideration of the variety of hardware used in non-PoW blockchains, this analysis defines two approaches to estimating how hardware is used:

Minimum hardware requirements: For a given protocol, it is assumed that the hardware consists of what is defined in the applicable stated minimum system requirements (where available).

Cloud-based: As an alternate estimate, it is assumed that protocols are run on identical hyperscale cloud servers, as has been found in a number of previous surveys in the market.

Due to the limited literature available on hardware disposal policies for hyperscale cloud providers, this analysis does not attempt to estimate the embodied carbon and e-waste using the cloud-based methodology. Instead, the minimum hardware requirements approach is detailed below.

Minimum hardware requirements

To estimate the embodied carbon and e-waste that are generated through non-PoW blockchain protocols, it is important to first define a counterfactual scenario, so that only the additional impact of the blockchain protocol is attributed to the protocol in question. For the purposes of this analysis, we assume that in the counterfactual scenario, in a world without the blockchain protocol in question, the hardware being used would not have been bought or produced. Therefore, the analysis attributes 100% of the embodied carbon and e-waste to the respective protocol.[1]

For each blockchain protocol, the minimum hardware requirements are identified and then cross-referenced with a piece of hardware that would satisfy the minimum requirements. Lifecycle assessment standards for each piece of hardware are then used to identify the embodied carbon and the impact in terms of kilograms of e-waste for one piece of hardware. These numbers are multiplied by the numbers of nodes in each blockchain protocol and divided by the number of transactions to get a comparative figure for the blockchain protocols included in the calculation.

1. In practice, the hardware being used for validation serves multiple uses, and alternative approaches could be selected to attribute a share of impact based on utilization.

Assumptions

The average piece of equipment is assumed to be discarded after five years [17].

Minimum specifications are used where available. If not available, an average of other protocols is used and indicated in the results.

As opposed to PoW blockchains, the consensus mechanism does not aim to augment computing power, and the hardware is not run at a consistently and excessively high utilization. The analysis assumes that the hardware lifetime is not shortened compared to standard usage of the hardware.

The end-of-life stage is not modeled and does not take potential reuse or recycling into consideration, therefore providing an upper-bound estimate of e-waste generation.

Differences in Life Cycle Assessment (LCA) methodologies for different hardware are ignored, and it is assumed that the results are comparable across LCA studies.

Blockchain Sustainability Framework: Assessment results

The results of the analysis for Stellar are summarized below.

Program	Estimated yearly electricity use (kWh)	Electricity use per transaction/API request (Wh/txn)	Estimated yearly emissions (kg CO_2e/yr)	Emissions per transaction/API request (g CO_2e/txn)
Stellar Core	261,435	0.173	94,098	0.062
Horizon API	219,889	0.000229	85,181	0.0000886

Table 14. Results of electricity use and carbon emissions from electricity for Stellar Core and Horizon API, part of the Stellar network.

(Note: Calculations are based on node types required for the ongoing operation of the protocol. Transaction types and node types may vary.)

Factors Affecting Future Blockchain Sustainability

While the Framework provides a snapshot in time of the environmental impacts of a blockchain protocol, it is important to recognize that different factors may influence the environmental impact in the future. Below are key macro trends that may alter the environmental impact of blockchain technologies: energy system decarbonization; hardware/software improvements; and how blockchain technologies scale.

5.1. Energy system decarbonization

5.1.1. The impact of global energy grid decarbonization on blockchain

The carbon footprint of blockchain technology depends on the carbon intensity of the electricity which powers it. The energy mix and therefore emissions associated with power generation differs by country or region, usually linked to economic status, natural resource availability and government policy. Currently, public climate and energy policy internationally implies that power generation globally will likely decarbonize with time as renewable energy continues to grow as a proportion of total power generation.

If the world meets the Paris Agreement's 1.5-degree scenario then by 2050 the power system will have been nearly entirely decarbonized. However, it is also clear that for the next 10 years power globally will still be largely dependent on fossil fuels, and it cannot be guaranteed that all countries that signed the Paris Agreement will meet these ambitious commitments. Two key takeaways emerge:

The electricity use of blockchain in the short to medium-term cannot be ignored by referencing long-term decarbonization of the grid. What drives climate change and impact is the amount of GHG emitted in total, not in any single future year, and the pathway to emissions reduction is as important as the target year for net zero.

Success in reaching net zero requires management of energy demand, as well as increasing the proportion of zero GHG energy sources. Leading models of pathways to net zero, such as the IEA's Net Zero by 2050 model [25], make assumptions on future state energy demand. If energy demand exceeds this in reality, this may impact society's ability to reach net zero by around mid-century.

Therefore, while the emissions intensity of blockchain may decrease over time due to external factors, the electricity use of blockchain technology does matter, particularly if blockchain-based digital currencies become more mainstream—in this scenario waiting for a green energy grid will mean contributing significantly to overall emissions.

5.1.2. The impact of blockchain on decarbonization

On the one hand, academics are projecting that growth in PoW protocols such as Bitcoin could increase the longevity of fossil fuel utilization, which would otherwise be discontinued, to meet excess demand from miners. For example, last year a cryptocurrency mining operation in central New York reopened a shuttered fossil fuel power plant to power 15,300 computer servers used to mine bitcoin.

On the other hand, some analysts project [26] that growth in the Bitcoin network would do quite the opposite, and could result in a more rapid rollout of renewables. This is based on the assumption that Bitcoin miners effectively operate as an electricity buyer of last resort, purchasing the cheapest energy source they have access to without limit, as long as it is economically viable to do so. Renewables are increasingly becoming the cheapest source of electricity in certain locations, therefore Bitcoin miners could indirectly support investment into the roll-out of renewables. However, further attribution analysis is required to understand to what extent cryptocurrency mining is supporting the roll-out of renewables that would otherwise not be built, versus taking clean power that could be used to decarbonize other sectors (see Section 5.3. for more detail on this topic).

In a similar vein, Bitcoin mining has been credited with helping US oil and gas producers cut the emissions associated with flaring. By utilizing on-site generation of power for Bitcoin mining, producers are able to economically invest in capturing excess natural gas (waste methane) to power their blockchain mining hardware, reducing emissions associated with gas flaring[1]. Further research is required to understand the scale to which this is currently applied, and what existing processes mining might be displacing, in order to provide a meaningful estimate of avoided emissions attributable to cryptocurrency mining through this approach. Regardless of whether renewable or nonrenewable energy is used, it is likely more beneficial that less energy is used overall.

5.2. Hardware/software improvements

Proof-of-Stake (PoS)

The ideal setup for PoS and other consensus mechanisms is to have a dedicated computer for staking, limiting additional processes running on the same hardware. Until now, hardware computational power has followed Moore's law as computational power has become significantly more efficient over time. While Moore's law, by the strictest definition, means the doubling of chip densities every two years, computational power may not consistently improve at this pace. This should be taken into consideration when discussing the electricity use of PoS and other consensus mechanisms as it will impact energy use as the efficiency of validating hardware improves.

Moore's Law

Moore's law is the observation that the number of transistors in a dense integrated circuit (IC) doubles about every two years. This phenomenon suggests that computational progress will become significantly faster, smaller, and more efficient over time.

Proof-of-Work (PoW)

Unlike proof-of-stake (PoS) and other consensus mechanisms, further increasing the energy efficiency of mining hardware would not reduce a PoW blockchain's electricity requirements in the long term. Competition in the mining hardware market, resulting from the popularity of cryptocurrencies, has dramatically increased the energy efficiency of mining hardware in the last decade.

5.3. Bitcoin as a buyer of last resort for electricity

1.Demand and supply in the electricity system

Electricity systems should balance out supply and demand to avoid blackouts. Depending on the electricity demand at a certain time, certain electricity generation facilities will be shut off or turned on to match the demand. The electricity mix of a network, therefore, has a variety of different electricity generation methods to meet demand. Traditional electricity generation derives energy from an energy store—some electricity sources such as hydropower or coal plants can be easily ramped up or down depending on demand while other sources, such as nuclear power, tend to provide a stable base energy supply. Renewable electricity on the other hand is generated from intermittent energy flows (such as wind, solar, or hydropower). In an electricity system with high levels of renewable energy the excess energy that is generated during peak times either needs to be stored or the generation needs to be curtailed. The excess energy can be stored in batteries, pump hydro storage, or turned into a different type of energy vector, such as hydrogen. These solutions are sub-optimal as technological solutions such as batteries and hydrogen are not yet commercially ready at a large scale, and pump hydro storage is restricted to certain geographical locations that are mountainous. In areas where excess electricity is generated and storage is limited, Bitcoin proof-of-work mining can serve as a user of that excess electricity.

1. Gas flaring: the burning of natural gas associated with oil extraction.

2.Bitcoin mining can be located where there is excess generating capacity

Bitcoin mining can be co-located where there is excess electricity generating capacity, thus acting as a buffer to balance out the supply and demand of electricity. For example, Bitcoin miners could enter into power purchase agreements (PPA) with power producers to utilize excess capacity during periods of low energy demand. The total emissions associated with Bitcoin mining vary depending on whether renewable electricity is used, or if the electricity is generated from fossil fuels.

3.The context of renewables

Overall, in 2020 about 39% of all electricity used to mine proof-of-work cryptocurrencies was from renewable sources [1] relative to renewables making up 28% of worldwide electricity generation [27]. This indicates that Bitcoin miners use a higher proportion of renewable electricity than the global average. The latest published distribution of Bitcoin mining attributes mining to different countries, but not to individual regions. This does not indicate whether renewable excess electricity is used and can only be viewed as a general indication that Bitcoin miners are more likely in countries that use a higher percentage of renewable energy.

Instead, incidental examples show the relationship between excess renewable energy and Bitcoin mining as a buyer of last resort. By buying the excess renewable energy that would otherwise have to have been curtailed renewable energy generation is made more profitable. At the same time, the attributable emissions for Bitcoin mining decrease as an increased proportion of renewable energy is used to power the operations.

4.How did this methodology treat emissions associated with this?

This methodology takes the grid emission factor to estimate greenhouse gas emissions and therefore takes an average grid emission factor for a region. This might slightly over-or underestimate emissions on a regional basis. For example, for regions with a higher proportion of renewable energy being used to mine Bitcoin, calculated emissions might be slightly higher than actual emissions. Bitcoin mining that uses renewable excess electricity is therefore not accounted for in this methodology. Additionally, electricity generation through flaring of methane is not assessed in this methodology as the emissions would have occurred in any case, generating equal or even greater emissions (see Section 5).

5.4. Scaling of blockchain technology

Blockchain technology has rapidly scaled in the last several years and is projected to grow to an even larger audience across industries and countries. A significant portion of this expansion can be attributed to the growth of cryptocurrency trading activity and other financial activity around the assets. With startups receiving greater venture capital funding, an increase in governmental guidance, and convergence of blockchain with other technology such as AI/ML or IoT, blockchain-related innovation is expected to grow in the coming years.

5.4.1. Marginal electricity use of one additional transaction

Marginal electricity use for one additional transaction is a measurement of the additional electrical energy used to transition from N to N+1 transactions per unit time, where N is the current average number of transactions per unit time. This may be used to discover differences in the electricity consumption of blockchain networks in the event that they do not scale linearly with an increase in transactions. Although not measured quantitatively in this report, it could be a useful metric for future research.

How can marginal electricity use per additional transaction be assessed?

The first metric defined in the Framework, **electricity use per transaction**, assumes that the overall electricity use of the blockchain system can be evenly divided by the number of transactions managed by the system. Normalizing electricity use in this way serves as a useful method to measure a blockchain protocol, by factoring in the relative scale and uptake of the protocol.

However, the electricity use of blockchain systems rarely scales entirely linearly with increased transactions recorded per unit of time. This methodology, therefore, defines an additional metric, **marginal electricity use for one additional transaction**, which examines the change in electricity use at the current transaction volume and how the makeup of different blockchain protocols influences energy use under an increase of one transaction. This can be particularly interesting for stakeholders that are considering establishing services on a blockchain but are concerned about the associated marginal increase in electricity use that their transactions would have on the blockchain.

To assess protocols against this metric in a quantitative fashion, it is assumed energy use varies linearly over a small change in the number of transactions. This assumption is tested by plotting the electricity usage of a protocol over a certain time period against the number of transactions of the protocol in the same time period. The proposed metric therefore aims to showcase the electricity use of the blockchain against the number of transactions completed per second on a blockchain, examining whether or not there is a relationship between the two variables.

This analysis is complemented by a qualitative analysis that identifies how the maturity and set-up of a blockchain contribute to increased electricity use.

It is important to note that this discusses the marginal electricity use of one additional transaction. While for small changes in transactions a linear change in electricity use can be assumed, this does not necessarily hold true for order of magnitude changes in the transaction rate. Frequently, the electricity use per transaction of different blockchain protocols is scaled up to represent the transaction levels of a traditional payments network by assuming a linear increase in energy use. This is not the intent of this metric, its sole purpose is to assess the short-term implications in terms of energy use with a marginal increase in transactions.

5.5 Security vs. energy use

As briefly discussed above, a focus on the Blockchain Trilemma may be valuable to reiterate the importance of security as blockchain networks scale. Any improvement in scalability, decentralization, or energy efficiency may have a corresponding impact on network security. For example, from an energy and scalability point-of-view, only one node is ideal; however, that leads to decentralization and potential security vulnerabilities. On the other hand, requiring consensus from 10,000 full validating nodes will not be as scalable or energy efficient as one node, but it will certainly be more decentralized.

As in any business context—security needs will vary based on the needs of the organization. Government organizations or those in highly regulated industries have a very low tolerance for security breaches and may be willing to trade off on the aforementioned components of the blockchain trilemma. As such, the results of any analysis of the electricity consumption or greenhouse gas (GHG) emissions of a blockchain protocol should be considered in the greater business context—and if a blockchain is chosen specifically because of some feature besides security, the security tradeoffs should be evaluated.

It should be noted that there is no strict definition of what constitutes a secure blockchain. Some may claim that decentralization of nodes and computing power is of leading importance to security while others may argue that you only need a specific threshold of unrelated participants to maintain security and that other aspects of the blockchain are more important. Regardless, security should be considered on all levels of a platform: at the protocol level, data level, and network level, including across different blockchains and when interacting with legacy systems or physical devices. Many security breaches occur because simple security measures were not taken and thus those breaches could often have been easily avoided.

There is an ongoing conversation about which consensus mechanisms are more useful or more secure. Ultimately, the question of which blockchain networks are most secure will reveal itself with time and with network expansion—as the “moneypot” for malicious actors increases, vulnerabilities in blockchain networks will be revealed and exploited. Market participants will likely continue to converge on an ideal state where security, decentralization, scalability, and sustainability can be maximized.

5.6. Regulatory environment

The regulatory environment surrounding cryptocurrencies has often been unclear, and the rules vary widely across jurisdictions. Some countries do not allow any cryptocurrency trading or mining, some encourage it and have even made it legal tender, and others provide very little guidance at all.

From a United States perspective, it has the challenge of balancing the competing priorities of allowing for innovation but maintaining security and investor trust. Not only that, there are multiple organizations that may regulate cryptocurrencies—these include the Securities Exchange Commission (SEC), The Commodity Futures Trading Commission (CFTC), the Office of Foreign Assets Control (OFAC), and the Internal Revenue Service (IRS), among others. To add to the undetermined regulations, states and local governments may have separate regulations from the organizations mentioned above. Maintaining regulatory consistency among so many governmental entities will likely remain a challenge; however, there has been some recent progress worth mentioning.

On March 9, 2022, the US government released an Executive Order on Ensuring Responsible Development of Digital Assets, which outlines “the first ever, whole-of-government approach to addressing the risks and harnessing the potential benefits of digital assets and their underlying technology” [28]. The Executive Order focuses on key topics of consumer and investor protection, financial stability, illicit finance, US leadership in the global financial system and economic competitiveness, financial inclusion, and responsible innovation. Notably, it specifically mentions the potential for digital assets to “advance or tackle” climate change as well as the impact that they may have on climate change themselves. This report may be a helpful first step in understanding the climate impact of digital currencies.

On March 21, 2022, the SEC gave initial approval to a new rule that would require public companies to disclose both their emissions (Scope 1, Scope 2, and in some instances Scope 3) as well as the risks that climate change poses to their business—indicating the importance the SEC is placing on ESG measures [29]. Many companies already disclose these emissions data voluntarily; however, it demonstrates the greater trend that is occurring in the regulatory environment—policy makers are interested in the environmental impact that companies and technologies might have on the world. The public and transparent nature of most digital assets make them well-suited for providing energy-related information to interested parties.

It should also be noted that, in March 2022, the European Parliament’s Committee on Economic and Monetary Affairs nearly voted for a version of the Markets in Crypto Assets bill that would have effectively banned proof-of-work-based cryptocurrencies within the EU. The fact that the more restrictive version of the bill was almost passed demonstrates the concern that many regulators have regarding the environmental impact of cryptocurrencies.

Concluding remarks

It is evident that participants in many blockchain networks are working hard to develop blockchains that have low levels of emissions or that are carbon neutral. It is likely that this trend will continue and the increased transparency around blockchain networks will continue to help drive emissions reductions on a per transaction basis. There are several key observations that can be drawn from the application of the Framework in this report.

Sustainability should be a core value of emerging blockchain technology developers: It is important to establish methods to assess the sustainability of new technologies as they develop to help guide them so that as they grow they do not lock in adverse impacts.

Blockchain technology does not necessitate the high environmental burden that some may perceive it to. Some blockchains generally require more energy to function, but it may be a tradeoff for higher security, scalability, or decentralization. The usefulness of different consensus mechanisms is a subjective and ongoing conversation among industry participants, and each protocol has unique advantages that should not be discounted.

Blockchain may offer benefits to aspects of the existing financial system without an environmental trade off. For example, blockchain networks can provide near-instant transaction settlement, open and transparent international trade, and smart contract capabilities, at a potentially reduced environmental footprint when compared to legacy financial processes. The total impact of these blockchain solutions is dependent on the technology stack that is selected and the type(s) of energy sources, which can be estimated using the methodologies in the Framework. It should be noted that blockchain is not necessarily replacing legacy financial systems, but rather can be used to augment them with new capabilities.

Additional sustainability and broader ESG indicators are worthy of future quantification. This report focused primarily on two metrics that were of high importance and high feasibility for measurement: electricity use and carbon emissions. Future research can consider quantifying the impact of some or all of the following: embodied carbon, electronic waste, environmental policy, water use, energy security, or biodiversity and land use. Further, broader social and governance impacts may be considered—these could include measurements for global financial inclusion, governance and risk management, business ethics, or responsible product innovation.

Immediate actions can be taken by market participants to estimate and mitigate their environmental impact. Market participants can continue efforts to source energy directly from renewables and to improve overall response to energy demand (see Sections 5.1.2 and 5.1.3). Blockchain networks and corporations alike should continue to seek to reduce their energy consumption in the near term and incorporate environmental considerations into how they engineer future iterations of blockchain networks and the applications built on top of them. One other action that may be taken to reduce environmental impact is to offset calculated emissions with purchases of high quality carbon credits or Renewable Energy Credits (RECs), as described in Section 3.2.4 of the report.

Sustainability is just one component in the overall assessment of a blockchain network. Scalability, security, and decentralization are other core features to consider. Furthermore, users may value smart contract compatibility, privacy, or extremely fast transaction time over other considerations. As such, the results of this report should be considered in the greater context of the utility of the platform being used.

Appendices

Appendix 1: Further boundaries for analysis

To expand on the assumptions stated above within Section 3 and the subsection titled “Methodological limitations and areas for further work”—namely that the accuracy, availability, and scope of this report may be limited—there are other boundaries worth mentioning and which may be iterated upon in future research:

- There are a large number of blockchain protocols and types available in the market, and not all of them are considered. Notable exclusions are private, permissionless blockchains.
- Despite the efforts to quantify and compare the electricity consumption and greenhouse gas (GHG) emissions of blockchain protocols and legacy financial processes, the comparison is not apples-to-apples. Each blockchain and legacy financial system provides different capabilities, and as such, whichever option may be better will remain to be somewhat subjective.
- There is no hard evidence that the blockchains evaluated can actually scale up to the size of the legacy financial companies evaluated and remain secure and efficient while doing so.
- Archive nodes or other nodes not critical to the functioning of the blockchain are not considered in the electricity consumption metrics. Further, only two nodes were measured for the direct PoS and FBA blockchain measurements.
- As mentioned earlier, the methodology does not quantify the electricity or GHG impact of applications built around the blockchain protocols, the impact of APIs, the impact of layer 2 solutions, the foundations supporting the protocols, or the impact of smart contracts or the different types of transactions which may occur.
- As described throughout the report, the comparison of legacy financial systems to blockchain protocols is not an apples-to-apples comparison. Future research should work to quantify the settlement layer of financial transactions in addition to the payments layer which was described in this report. Further, the comparison of a complete legacy financial system (settlement and payments layer) could be compared to a complete blockchain system (both layer 1 and layer 2 protocols) for a more robust analysis.
- Also mentioned earlier, this report does not quantify ESG impacts that were deemed lower importance or lower feasibility, including but not limited to: water use, energy security, biodiversity and land use, and others as illustrated in Section 3.1.
- The development of the report did not include any large scale surveys of blockchain validators or other network participants.

PwC has not audited or verified the information provided to it within the scope of the work, regardless of its source.

- PwC cannot guarantee that PwC got to know all relevant documentation or information that may be in existence and therefore cannot comment on the completeness of the documentation or information made available to PwC. Any documentation or information brought to PwC attention subsequent to the date of this study may require PwC to adjust and qualify this study accordingly.

Appendices

Appendix 2: Glossary

- **Block**: A set of several operations grouped together, validated by the network, and linked to the previous block of operations cryptographically. A block contains other information such as the current block number, information about the previous block, and the time at which it was validated.
- **Block Header**: Used to identify a particular block in the blockchain. It gives a summary of that block in terms of metadata.
- **Blockchain**: Data structure that groups information into immutable containers called blocks, chains them together in an order-preserving way that only allows appending (but not deleting or editing). This chain of blocks (or blockchain) is replicated multiple times in a distributed (peer-to-peer) network, as every peer keeps a copy of the current snapshot of the blockchain. Registered data can stand for e.g., transactions, loans or digital art. Blockchain is also a network of exchange of data and value.
- **Bonding**: The “locking” of tokens required to stake and receive staking rewards on a blockchain.
- **Byzantine Fault Tolerance**: In the context of distributed computing, it is the ability of a system to operate even if some nodes fail or act maliciously.
- **Carbon credits**: Certificates purchased that certify that a certain amount of emitted carbon emissions have been canceled out by a reduction of carbon emissions in a different context.
- **Consensus protocol/mechanism**: The protocol defining the rules of validation for new blocks to form a unique chain. It is specific to each blockchain. In this report, “blockchain network” is used interchangeably with “blockchain protocol”.
- **Cryptocurrency**: A digital currency associated with a (public) blockchain and linked to its consensus protocol.
- **Electronic waste (e-waste)**: Electronic equipment that has been discarded.
- **Embodied carbon**: The emissions during the production process of hardware used to run the blockchain.
- **Greenhouse gas (GHG) emissions**: GHG emissions in this context are referred to greenhouse gasses emitted during the creation and usage of products and services.
- **Hash**: An output from hash algorithms, that produce unique and fixed length string.
- **Hashing difficulty**: A measure of difficulty to find a hash below a given target i.e., in broad terms difficulty of mining in a proof-of-work consensus mechanism.
- **Hash rate**: A measure of the number of hashes being computed per unit time. In broader terms it is the computational power used by a proof-of-work network for its transactions.
- **Layer 2**: A framework built as an extension to the main blockchain and relies on it for security. Its main goal is to address the scaling difficulties.
- **Mempool**: A collection of unconfirmed transactions that are still haven’t been added to the blockchain.
- **Net Zero**: Net zero refers to a state in which the greenhouse gasses going into the atmosphere are balanced by the removal of greenhouse gasses out of the atmosphere.
- **Non-Fungible Token (NFT)**: Cryptographic assets on a blockchain which have unique identification codes and for which unique proof of ownership can be provided. For example, a NFT of a picture cannot be copied and distributed as the original NFT picture is cryptographically unique, a property which can be proven to others.
- **Node**: A node is a peer (a machine, physical or virtual) on the peer-to-peer network. It keeps a copy of the current version of the chain and propagates the blocks containing all operations to the other peers. A node is not necessarily a validator, but a validator is always associated with one or more nodes.
- **Partitioning**: The storage of part of blockchain rather than the full record of transactions and blocks.

- **Point of sale device**: Typically a device that handles the physical payment that must occur at the time and place of a transaction; for example, a cash register, kiosk, or cell phone can serve as a point of sale device.
- **Proof-of-Stake (PoS)**: Validators are selected randomly based on their pro rata quantity of holdings in the blockchain cryptocurrency. Generally, these validators are known as “stakers”.
- **Proof-of-Work (PoW)**: Validators are selected based on their capacity to solve computational problems. They are called miners.
- **Pruning**: Pruning in nodes removes non-critical blockchain information and retains information necessary for the node to function.
- **Quorum**: A minimum number of stakeholders required to be present at an event to make that event valid.
- **Quorum slice**: A subset of quorum required to make a particular node agree in the Stellar Consensus Protocol.
- **Renewable Energy Credits**: Also known as Renewable Energy Certificates, RECs are tradable credits that certify that the owner has bought a certain amount of renewable electricity.
- **Rewards**: Earned through mining, validating, or staking and usually result in some amount of the blockchain network’s native token.
- **Side chains**: They are individual blockchains connected to a main blockchain.
- **Slashing**: A penalty for not acting in the best interests of the network and results in the loss of some or all of a bonded stake.
- **Smart contract**: Self-executing contract with the terms of the agreement between parties written into lines of code, which exists on a decentralized network.
- **Verifiable Random Function**: A cryptographic function that produces random output for a particular node.
- **Wallet**: A device or program that allows users to store and transfer cryptocurrency.

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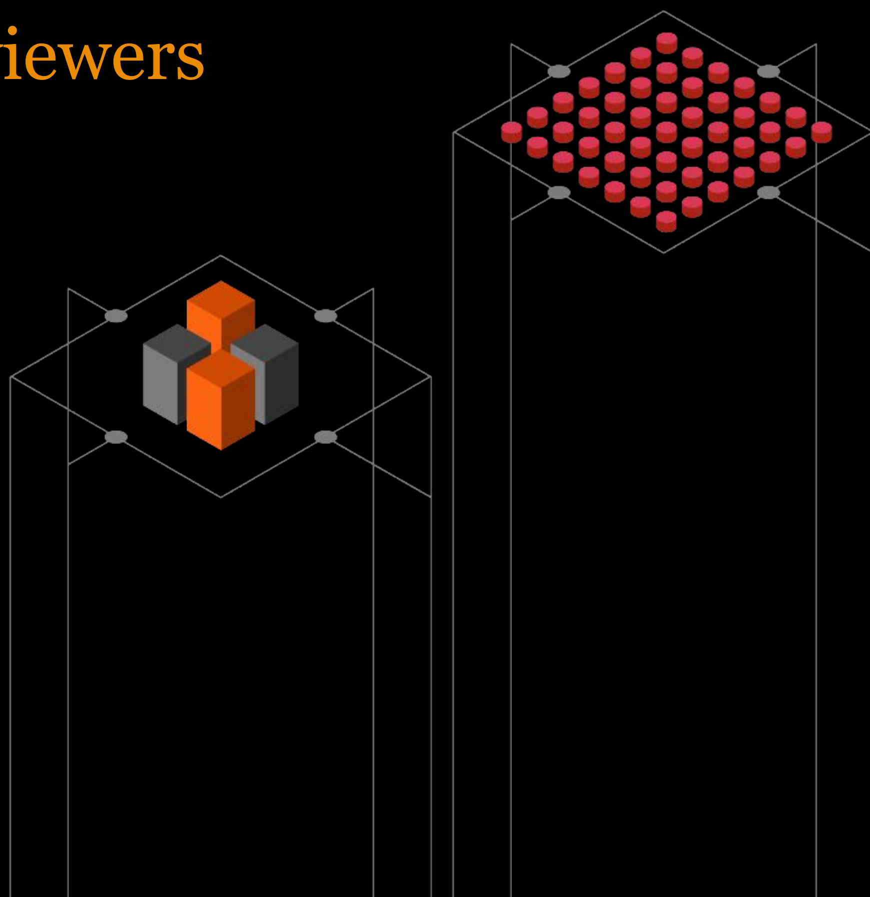

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