Economic and social sustainability of legacy blockchain for non-crypto use cases: a reality check

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Abstract: Predicted to be a $3+ trillion industry by 2030, blockchain has still not achieved commercial viability beyond its stupendous success in enabling a multi-trillion cryptocurrency industry. Very high transaction cost and vulnerability to centralisation limits blockchain's full potential. As cryptocurrency thrives, blockchain struggles to find its rightful place. This paper looks at the public blockchain and its failed attempts at non-crypto use cases to arrive at an accurate diagnosis of what's ailing. Based on a de novo review of the literature, this study formulates and supports a hypothesis on blockchain's economic and social unsustainability. Although economic sustainability trumps environmental sustainability all the time, peer-reviewed literature is mostly silent on its economic sustainability, no one conducts environment damaging activity unless there is economic benefit. So far non-crypto use cases of blockchain have shown little or no economic benefit. Testing our hypothesis may help blockchain researchers define the future generation sustainable decentralised solutions.

Keywords: consensus; decentralisation; economic sustainability; Ethereum; future blockchain; social sustainability; sustainable blockchain; transaction cost.

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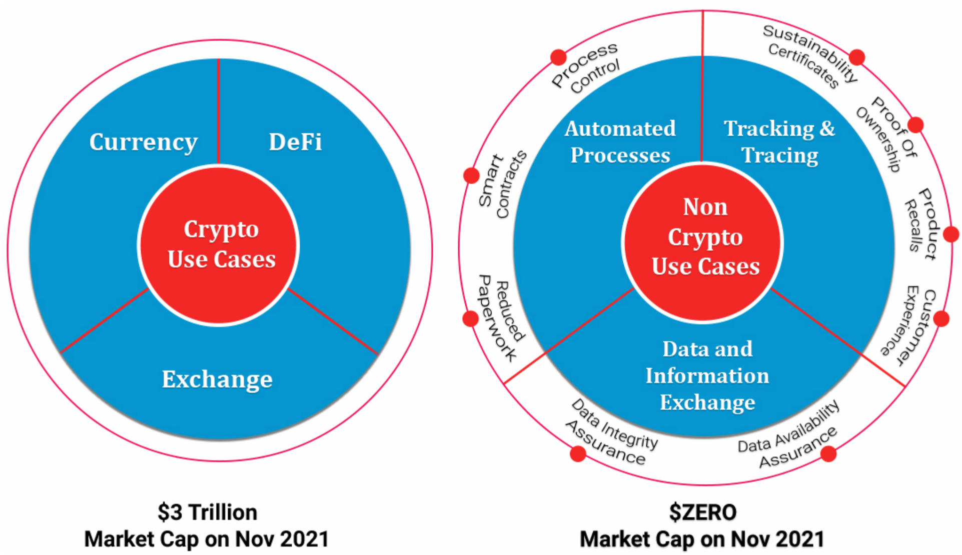
1 Introduction

In 2021 cryptocurrency market cap hit $3 trillion (Horch et al., 2022), a feat no technology in the history has achieved within a short span of just over a dozen years that blockchain has existed. There is absolutely no doubt that blockchain is here to stay, and no hesitation in concluding that blockchain's cryptocurrency use case is indeed commercially successful. However, the non-crypto use cases of blockchain envisioned to make blockchain omnipresent in human computer interactions (Fröhlich et al., 2022) have so far fumbled as we are not aware of a single commercially successful non-crypto use case that is currently revenue generating or significantly contributing to blockchain's total market cap. Hence as illustrated in Figure 1, virtually all of blockchain's commercial success so far is attributed to its crypto use cases (viz., DeFi, exchanges and currency) only, and contribution of non-crypto uses remains almost zero. In reviewing the reasons de novo and formulating a strategy to build the next generation blockchain, this paper's focus is public or permissionless blockchain, and private (permissioned) or consortium blockchains are not scoped.

Figure 1 Commercial success of blockchain use cases: crypto vs. non-crypto (see online version for colours)



Source: Horch et al. (2022) and Zhao (2022)

Blockchain and cryptocurrency are inseparably linked. As much as a decentralised form of money simply cannot exist without the security provided to it by blockchain, a public blockchain cannot be created without giving people incentives to create it (van Haaren Duijn et al., 2022). Decentralised currency is that incentive.

Before delving into the question of economic and social sustainability of blockchain it is pertinent to define relevant technical terms:

> "Blockchain is a decentralized ledger technology that immutably links a growing list of publicly accessible records called blocks in a chain, using cryptographic hashes that require consensus of majority of record validating peer nodes in a peer-to-peer public network incentivized with tokenized rewards for contributing their resources for validating the blocks." (AlgoShare, 2019b)

The following essential elements make the definition of a public blockchain complete:

1. decentralised ledger
2. immutable chain of publicly accessible records
3. cryptographic hashing
4. consensus of peers for validating records
5. incentivised public network.

> "*A blockchain network* is a technical infrastructure that allows applications to access ledger and smart contract services. Smart contracts are primarily used to originate transactions, which are then transmitted to each peer node in the network and recorded immutably on their copy of the ledger. In short, a blockchain network is the blockchain ledger plus everyone contributing to that ledger."

> "*A blockchain protocol* is the rules that govern the blockchain network."

> "*Blockchain stakeholders* are entities that bank on decentralized governance of a network who are incentivized for their participation in the network via tokens in the form of cryptocurrency, and include cryptocurrency end-users, investors, transaction validators or miners, developers, market enablers, researchers, and financial regulatory agents. They are key components of the blockchain ecosystem and major determinants of blockchains' future direction. Analysing viewpoints of each stakeholder group help understand the impact of blockchain to the financial system and to society at large."

> "*Mining* is the process of verifying new transactions to the blockchain's digital currency system in compliance with a consensus algorithm that rewards a miner with new cryptocurrency tokens for the miner's participation in the blockchain ecosystem. It is essentially the way the network confirms new transactions and is a critical component of the blockchain ledger's maintenance and development."

> "*A consensus algorithm* is a fault-tolerant mechanism that is used in blockchain systems to achieve the necessary agreement on a single data value or a single state of the network among the peers in the network."

1.1 Research highlights

1. The transaction costs of current generation blockchains are too high to make them economically sustainable.
2. Economic and social sustainability of blockchain always trumps environmental sustainability rendering it moot.
3. Legacy blockchain systems are centralisation prone, and perfect decentralisation appears to be impossible.
4. Next generation blockchain must be economically and socially sustainable to make any inroads into much hyped non-crypto use cases.
5. This paper verbalises five rules that next generation blockchains can comply to render them sustainable.

1.2 Paper structure

The question of economic and social sustainability of blockchain is reviewed de novo in this paper and organised in nine sections. In pursuit of those objectives this paper adopts a methodology that first reviews the peer reviewed literature in Section 2, formulates a hypothesis to be supported with available evidence in Section 3, followed by peer-reviewed evidence to build and support the hypothesis in subsequent sections. Section 4 establishes clear understanding of what sustainability entails in the context of blockchain, and then Section 5 tries to explore reasons why blockchain has not been able to produce any successful production grade non-crypto use cases. Section 6 addresses the criticism and scepticism and presents a rebuttal to defend the pursuit of deliverance of blockchain's full potential. Section 7 proposes a rational strategy for modelling the next generation blockchain, while Section 8 highlights the limitations in interpreting the results of this research. Section 9 discusses conclusions and future outlook. We believe this is a maiden review of the economic and social sustainability of blockchain.

2 Literature review

Humongous body of evidence has accumulated in peer reviewed literature (Narayanaswamy et al., 2022) suggesting blockchain's potential utility in almost all walks of life (Li et al., 2018). From supply chain management (Dietrich et al., 2021) to healthcare (Esposito et al., 2018), security (Zhang et al., 2019), IoT (Dorri et al., 2017), finance (Treleaven et al., 2017), power distribution (Wang et al., 2020), energy sector (Teufel et al., 2019), governance (Tan et al., 2022), real estate (Shedroff, 2018), climate change (Chen, 2018), biopharma (Leach et al., 2022), drones (Lv et al., 2021) and countless other domains (Abou Jaoude and Saade, 2019), blockchain has been touted to become a game changer of sorts for the green revolution (Polas et al., 2022). However, in reality, blockchain has hardly made any tangible inroads into any non-crypto use cases, raising a question whether it is at all economically sustainable in use cases beyond cryptocurrency. If a solution is not commercially viable, there's no point studying its social and environmental sustainability. A sustainable blockchain use-case cannot be sustainable unless the blockchain itself is economically sustainable. Economic sustainability trumps social or environmental sustainability all the time. Any initiative, no matter how noble it is, if it is not economically viable it is rendered moot. No one conducts an environment damaging activity unless there is economic benefit. It is indeed surprising that there is so much literature on blockchain and environmental sustainability (Parmentola et al., 2022) and almost nothing on its economic sustainability.

3 Methodology: formulating and supporting a hypothesis

Any scientific journey should begin with formulating a clearly articulated hypothesis or problem statement, and then proceed with supporting it or dismissing it before peer researchers test and validate it. The principal objective of this research is to formulate a hypothesis and harvest available data to support it. The hypothesis that this paper frames and supports with scientific evidence is as follows:

> "The transaction costs of current generation blockchains are economically unsustainable and their decentralization is centralization prone."

The objective of this research is also to make the hypothesis available to a broader community of blockchain researchers for testing and proving or disproving the hypothesis to help shape the future of blockchain.

4 Understanding sustainability and its three barriers

The everyday meaning of the adjective 'sustainable' is simply being "able to be maintained at a certain rate or level" (Stevenson and Lindberg, 2010). The literal dictionary meaning of the term makes explicit what follows logically from the idea of using something for a purpose. A lifestyle, a way of doing things, is sustainable if most of the world's population could continue it for a long time without major adverse consequences. It is a potential dynamic equilibrium of some type (Heal, 2012). In the context of United Nation Development Programme (UNDP), a "sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs." *Hence it* is most often defined as meeting the needs of the present without compromising the ability of future generations to meet theirs (Tsalis et al., 2020). Sustainability means meeting our own needs without compromising the ability of future generations to meet their own needs. In addition to natural resources, we also need social and economic resources. Sustainability is not just environmentalism, but also encompasses social equity and economic concerns. It is the way an economy operates in a sustainable manner, protecting social and environmental elements. This is clearly enshrined in United Nation's 17 Sustainable Development Goals (SDGs) for 2030 adopted by 193 countries as a "blueprint to achieve a better and more sustainable future for all" (Emas, 2015). Sustainability is essentially what we want to happen indefinitely.

The 17 SDGs are integrated, recognising the fact that action in one area will affect outcomes in others, and that development must balance economic, social and environmental sustainability. Countries have committed to prioritise progress for those who are furthest behind. The SDGs are designed to end poverty, hunger, AIDS, and discrimination against women and girls. Creativity, know-how, technology and financial resources from all of the society is necessary to achieve the sustainability in every context (United Nations, 2020). From that perspective are blockchains sustainable? An answer to that question will go a long way in building the next generation blockchain.

Currently blockchain's only use cases that are commercially successful are cryptocurrency related. Beyond cryptocurrency, blockchain's economic, social and environmental sustainability is at best questionable. This is despite being aggressively pursued for all kinds of economic, social and environmental use cases (Sachs et al., 2021; Al-Megren et al., 2018). If a use case is not commercially viable, the question of its social and environmental sustainability will become a moot point. But ironically almost all sustainability literature on blockchain pertains to environmental sustainability without even considering whether it passes the economic and social sustainability barriers.

4.1 Economic sustainability

Economic sustainability is the first barrier that's a showstopper for any innovation to be adapted. If a solution is not commercially viable it simply culminates in its natural death. There is no question of exploring its social and environmental dimensions because no one will pursue a socially or environmentally adverse activity unless there is some economic benefit or a financial advantage in the pursuit. Blockchain's cryptocurrency use case remains a hot pursuit because of the overwhelming success of the crypto industry in recent years, and therefore qualifies an investigation into its social and environmental sustainability. But a review of the non-crypto use cases of blockchain tells us a completely different story that is hardly voiced in peer-reviewed literature, which often considers Ethereum synonymous with blockchain technology (Li and He, 2020). No matter what the use case, "Ethereum is the standard for smart contract" (Caldarelli, 2020) that remains the foundation of any non-crypto application. The cost of each transaction recorded on each node of the blockchain may not be of as much relevance when recording a token buy/sell transaction as long as there is a profit-making potential involved. But it is of huge relevance to a non-crypto use case when recording a smart contract transaction on blockchain, particularly when a comparable transaction on a legacy database costs almost nothing.

The notions of 'transactions' and 'costs' are the focus of the economic theory of transaction costs. The term transaction is used to describe the process of shifting a commodity or service unit, whereas transaction costs are the total amount of both monetary and non-monetary resources required to complete the transaction. The costs occur as a result of the combination of environmental uncertainty, limited rationality, expediency, and the asset-specific nature of the transfer.

Figure 2 Transaction cost of Ethereum 360 times higher than a conventional relational database (see online version for colours)

Source: Rimba et al. (2017)

A 2017 study by Rimba et al. was the first study that compared the cost of recording data on Ethereum blockchain against a legacy database, finding that the blockchain cost was

360 times (36,000%) higher than the conventional cost (Rimba et al., 2017) as depicted in Figure 2. They further estimated that the conventional Amazon servers must store the data for a mind boggling 197 years to reach a break-even point to justify the blockchain transaction. Moreover, those estimates were when the Ethereum price was in two digits. Now, with the Ethereum price being in four digits, the cost is astronomically prohibitive (Figure 3). While sustainable blockchain researchers mostly focus on blockchain's electricity consumption and its carbon footprint (Schinckus, 2020), or propose sustainability use cases (Yahaya et al., 2020), the humongous transaction cost, which makes it totally unsustainable, is often underplayed. Even if the carbon footprint hurdle is overcome in future, the transaction cost is unsurmountable. When the upcoming shift from proof-of-work (PoW) to proof-of-stake reduces carbon footprint of Ethereum, experts believe its transaction cost is not likely to come down (Gogo, 2022).

Figure 3 Historical ETH gas fee/transaction (see online version for colours)

Source: http://www.statista.com/statistics/1221821/gas-price-ethereum/

More recently Fabian and Weber published a cost analysis based on ten published studies and estimated mean Ethereum transaction cost of $1,010 in 2021 and in no case below $100, concluding use of a private network instead of blockchain in almost all scenarios (Fabian and Weber, 2022). As illustrated in Figure 3 the astronomically high 2022 transaction costs of Ethereum ranging between $474 and $28.8 may only support a transaction that's worth tens if not hundreds of thousands as a rare non-fungible token (NFT).

4.2 Social sustainability

Social good is something that benefits the largest number of people in the largest possible way, such as equality, inclusivity, clean air, clean water, healthcare, literacy, etc. The core of social sustainability of a blockchain lies in its inclusivity, equitability, and transparency, all of which depends on the extent of decentralisation it represents.

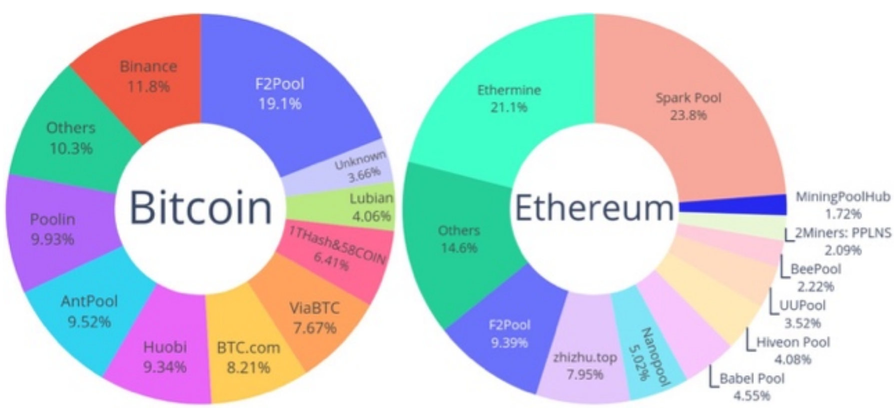
Robustness and sustainability of any decentralised blockchain system depends on the strength of the consensus algorithm it deploys.

No matter how much decentralisation is inherent in blockchain, human intervention will always work to centralise the power by one or the other means. Consensus algorithm is at the heart of such a power play. Since Satoshi Nakamoto's first disclosure of the PoW consensus algorithm in his Bitcoin blockchain white paper in 2008, several consensus protocols have been developed and deployed. But none can claim to be completely immune to a 51% attack. This is because:

> "Although blockchain, in theory, decentralizes power, it cannot completely stop human greed and craving for power from gaming the system. Pooling, syndication, cartelization are the names of the game." (AlgoShare, 2019a)

A 51% attack on a blockchain network is when a single entity or organisation or syndicate can control much of the hash rate, potentially causing a network disruption. In such a scenario, the attacker would have enough mining power to intentionally exclude or modify the ordering of transactions. They can send a transaction and then reverse it, making it appear as though they still had the coin they just spent. This vulnerability, known as double-spending, is the digital equivalent of a perfect counterfeit and the basic cryptographic hurdle the blockchain was built to overcome. A network vulnerable to double spending would quickly suffer a loss of confidence. 51% attackers can also prevent other miners from completing blocks, theoretically allowing them to monopolise the mining of new blocks and earn all the rewards. All cryptocurrencies that use distributed ledger blockchains are potentially vulnerable to 51% attacks (Bambrough, 2021), with Bitcoin itself suffering one in 2014 (Hern, 2014). While the debate on the most robust decentralised consensus algorithm goes on, the consensus protocol that sanitises a blockchain from 51% attack alludes. There seems to be no consensus on the perfect consensus protocol.

Figure 4 Consensus centralisation in Bitcoin and Ethereum (see online version for colours)



Source: Sai et al. (2021)

Centralisation, due to its simplicity, is a phenomenon that happens to any disciplined and organised system automatically (Beikverdi and Song, 2015). Bitcoin core developers once decided to lower the transaction fees unilaterally without discussing with the community (Gervais et al., 2014). Similar centralised control also exists in Ethereum (Bai et al., 2020). Core developers of blockchain have more decision-making power in the decision-making process and hence centralising the governance of blockchain (Sun et al., 2022).

As represented in Figure 4, currently four Bitcoin mining pools and just three Ethereum pools control these networks (Sai et al., 2021). Given the existing mining concentration, decentralisation seems to be impossible in blockchain. Theoretical discussions (Abadi and Brunnermeier, 2018) and empirical evidence show that complete decentralisation is an illusion (Sun et al., 2022). Several dominant miners can account for validation of most transactions in Bitcoin and Ethereum. Another report claims Ethereum is more centralised than Bitcoin (Lin et al., 2021). To alleviate the negative effects of collusions, Ethereum blockchain implemented new transaction fee mechanism in the London Fork in 2021, but it neither deters pooling, nor bribery (Sun, 2022).

4.2.1 Blockchain beats North Korea in centralisation

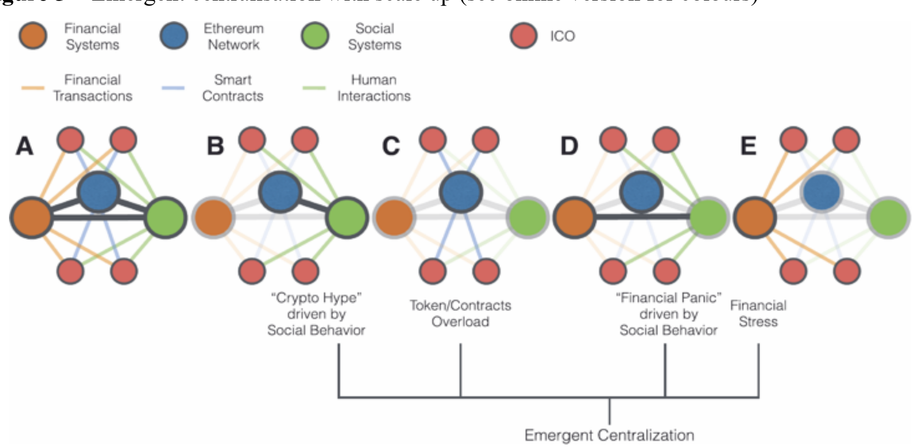
It is abundantly clear that legacy blockchain ecosystem is far from being perfectly decentralised. According to Guo et al. (2022) "wealth in crypto land is more concentrated than in North Korea where the inequality Gini coefficient is 0.86. The Gini coefficient for Bitcoin is an astonishing 0.88."

Unfortunately, in contrast to the regulated centralised legacy systems, the increasing centralisation of blockchain systems do not abide by any transparent regulations/ legislations. This could, in turn, lead to severe consequences on the fate and reputation of blockchain ecosystems.

4.2.2 Emergent centralisation: the decentralisation paradox

Apart from inherent nature of blockchain participants to amass control and accumulate power by hook or by crook, the growth of a network may also naturally propel itself towards centralisation in an expanding socio-technical system (Manlio and Baronchelli, 2019). Such 'emergent centralisation', as illustrated in Figure 5, is predictably inevitable if left to manipulation by powerful peers.

Figure 5 Emergent centralisation with scale up (see online version for colours)



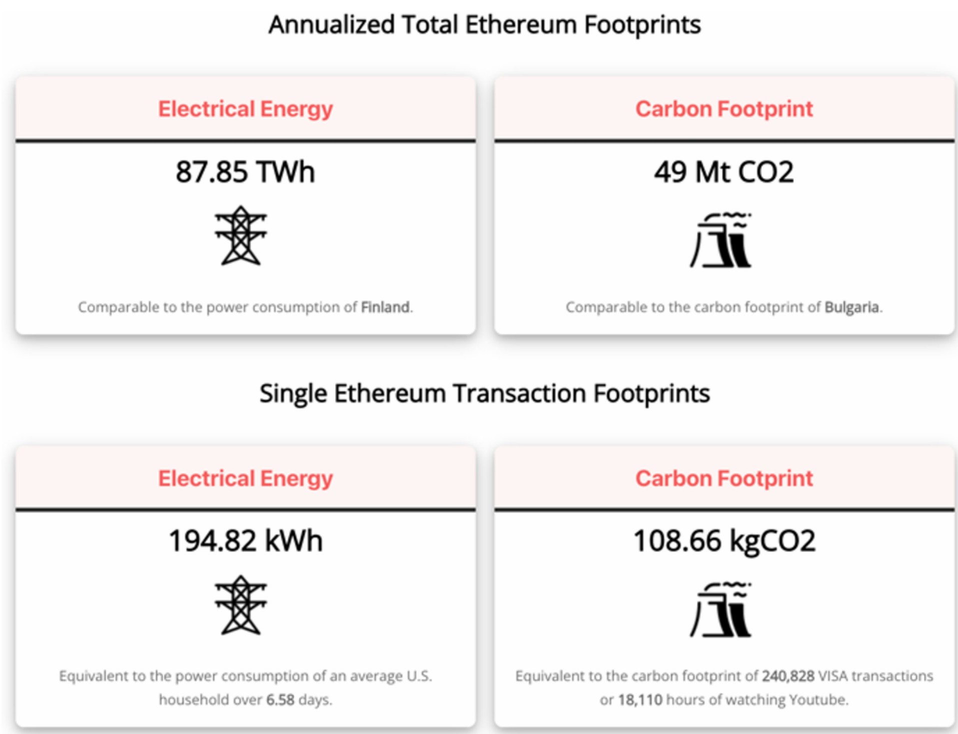
Source: Manlio and Baronchelli (2019)

Marginal cost is the cost of producing one extra unit of a particular good, which in case of blockchain represents the cost expended by a consensus-producing actor to produce one additional unit of consensus on the network. An economy of scale reduces marginal costs encouraging fewer producers and larger scale production which is inherently in opposition to the goal of decentralisation. Based on the capital costs, operating costs and opportunity costs, any system which aims to remain decentralised must aim to minimise the advantage of economies of scale when producing extra consensus or it will suffer from emergent centralisation as it grows.

4.2.3 Environmental sustainability

Ethereum is the most energy consuming blockchain after Bitcoin. It eats up at least a quarter to one third energy as Bitcoin does. A typical Ethereum transaction gobbles as much power as an average US household uses in almost a week leaving a carbon footprint larger than over 200,000 Visa transactions as illustrated in Figure 6.

Figure 6 Ethereum carbon footprint (see online version for colours)



Source: DIGICONOMIST.net (2022)

As illustrated in Figure 6, on 29th July 2022, Ethereum consumed 87.85 TWh of energy comparable to the power consumption of Finland and left 49 Mt of CO_2 as carbon footprint equivalent to Bulgaria (DIGICONOMIST.net, 2022). Ethereum has plans to change its PoW algorithm to an energy efficient proof-of-stake algorithm called Casper. This change would minimise energy consumption and will be implemented gradually according to the latest roadmap. For now, Ethereum is still running on PoW completely.

In its current state, the entire Ethereum network consumes more electricity than a number of countries.

With that level of carbon footprint and super high transaction costs can sustainability professionals justify smart contract deployment in utilities or renewable energy development seeking a more efficient way of pricing and selling clean power? Or can consumer products companies and retailers seeking a better way of validating supply-chain claims deploy blockchain? And can banks and insurance companies interested in verifying the provenance of minerals, commodities, or raw materials, justify smart contracts?

The real problem is, most entrepreneurs working on 'social good', 'sustainability' are social entrepreneurs and not blockchain experts. Almost all of them use Ethereum blockchain as their network backbone for proof-of-concept totally ignoring its prohibitory transaction costs. Can any solution based on Ethereum be sustainable or do 'social good?' Yet in the frenzy that blockchain has created, even most 'blockchain for good' challenges have judged Ethereum-based start-ups as winners. In 2020, European Commission's European Innovation Counsel awarded five million Euros each to six winners of 'blockchain for social good' (Digibyte, 2020) who were Ethereum researchers deploying Ethereum for sustainability driven applications. Unfortunately, most current 'social good' use cases piggyback on the most unsustainable blockchain. If a blockchain is not sustainable, it at least should not be an enemy of sustainability. That compels the critics to ask: will there at all be a blockchain for social good?

5 Why no production grade non-crypto dApps yet?

Most blockchain research focuses on scalability and speed of transactions, which we believe are already within reach. The dynamics of real-world use cases go beyond scalability and speed and hinge around creating a surplus value from each transaction recorded on the blockchain, and done so in perfectly democratic manner, leaving no scope for human manipulation. Blockchain researchers have been so focused on scalability and speed issues that the transaction cost and decentralisation dimensions of blockchain have mostly been ignored. While the former depends on the economics of each transaction and is a showstopper of sorts, the latter involves perfecting the blockchain's consensus mechanism, which are currently prone to pooling, syndication or some such centralisation. A less than perfect consensus mechanism cannot be perfectly decentralised to prevent 51% attacks.

5.1 Crypto dApps all the way

In July 2022, Dapp.com reported data on top 10 dApps (Figure 7). All those dApps represent crypto use cases (either DEX or DeFi), and none of them service a non-crypto use case (Dapp.com, 2022). The much-promised non-crypto use cases do not show up in the landscape of operational dApps. During a dozen years that blockchain has existed CB Insights reports 1,178 unicorn companies (Tracker, 2022), but none of them is based on non-crypto use case of blockchain.

Figure 7 Top 10 dApps in July 2022 (see online version for colours)

Source: Dapp.com (2022)

A joint study by the US Agency for International Development and Research and Learning (MERL) examined 43 blockchain projects and reported 0% success rate, and vendors did not call back when asked for the evidence (Orlowski, 2018). This finding was consistent with results reported by a subsequent study by British Blockchain Association (Naqvi and Hussain, 2020). Out of the 25 blockchain case studies that Arup published in 2019, the Bankex blockchain project WaterCoin was the only project that was estimated to reach TRL 7 the earliest, i.e., in 2020 (Gerber et al., 2019). But WaterCoin is now defunct, and none amongst Arup's reported 25 blockchain projects have seen the light of the day. Recently IBM shut down its super ambitious blockchain project we.trade launched in 2019 in collaboration with 12 European banks (Gooding, 2022). Sources report that IBM has cut its blockchain team down to almost nothing (Allison, 2021).

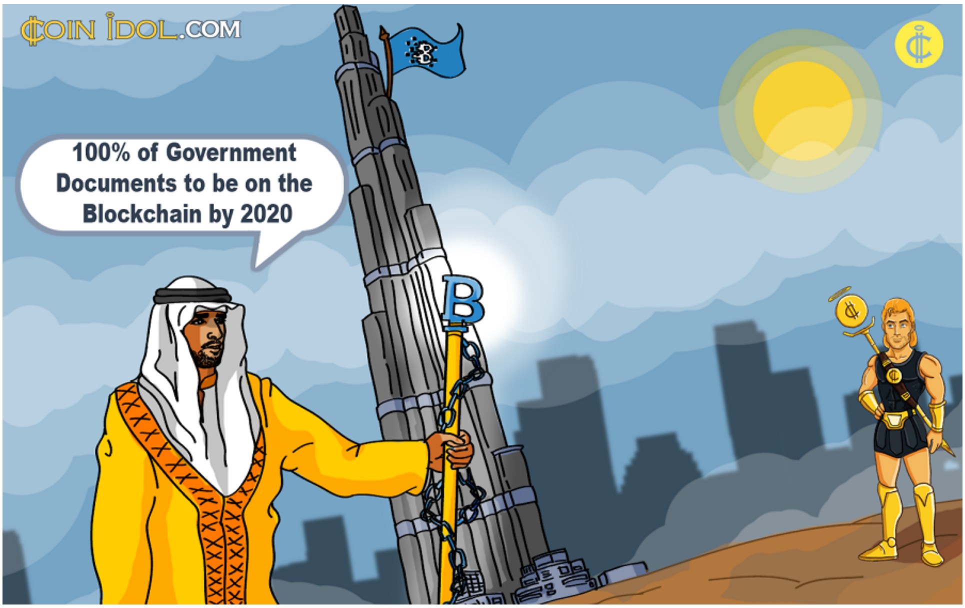
5.2 The curious case of Dubai and Estonia

After the launch of Ethereum in 2015 many blockchain initiatives were announced. Dubai became the first city to declare in 2016 that all government documents will be on blockchain by 2020 (Lyon, 2016) claiming:

> "The Dubai Blockchain Strategy will help Dubai achieve the vision of H.H. Sheikh Mohammed bin Rashid Al Maktoum by making 'Dubai the first city fully powered by blockchain by 2020' and make Dubai the happiest city on earth." (Digital Dubai, 2022)

Six years since the announcement there is no sign of blockchain making any real inroads into Dubai's governance system and authorities remain silent and non-responsive to the big announcement they made six years ago. However, two reports published earlier this year ensure that Dubai blockchain project is still alive (Baroudi and Benghida, 2022) albeit limiting it to implementing know your client (KYC) as a commercially justifiable use case (Khan et al., 2022) rather than the original claim of "100% government documents to be on blockchain by 2020" (Figure 8).

Figure 8 100% of government documents to be on the blockchain (see online version for colours)



Source: Coinidol.com

The blockchain situation of Estonia is even stranger. Countless peer-reviewed publications claim Estonia's primacy in blockchain (Vestergaard and Umayam, 2022; Clifton and Leslie, 2022; Narain, 2022), calling it "the digital republic secured by blockchain" (Martison, 2022). Some even claim that blockchain was invented in Estonia (Semenzin et al., 2022) even before Satoshi Nakamoto's 2008 disclosure (Nakamoto, 2008). The Estonian digital identity scheme uses keyless signature infrastructure (KSI) technology developed by Guardtime, much before the advent of blockchain. But neither they ever migrated their system to blockchain/DLT, nor did acknowledge the credibility of blockchain until 2018. On the contrary Guardtime was quoted predicting the fate of blockchain as: "they will eventually be assigned to the dustbin of history" (Raheman, 2019), before they eventually started branding their KSI hashing algorithm as KSI blockchain when the blockchain hype was in its prime. They continue to do so (Ali et al., 2022). However, in more recent publication on an ultra-scalable blockchain for asset tokenisation as KSI Cash, they shy away from precisely defining KSI (KSI in KSI Cash is not an acronym and stands for nothing, the name KSI Cash has been chosen by Guardtime for internal reasons) (Buldas et al., 2022). While several reports clarified that Gaurdtime's KSI (Jeffries, 2018) is not a blockchain (Consult Hyperion, 2017), including Estonia's own Tallinn-based institute first affirmed in 2018 that X-Road (the Estonian e-governance platform in question) is not blockchain-based (Kivimaki, 2018), and reiterated its conclusion in 2021 (Kivimaki, 2021), the debate still goes on (Martison, 2022).

5.3 Government blockchain projects

There is a long list of blockchain projects initiated by various governments for e-governance related use cases. The most mature of those projects include the land registry initiatives commenced in Georgia (Shang and Price, 2019) and Sweden (Gertrude, 2016) in 2016, in Moldova in 2017 (Pilkington et al., 2017) and a UNDP collaborative project in India using Ethereum (Oprunenco and Chami, 2018). None of them reached production grade deployment in 4–6 years that these projects have been active. An official final report from the developer of the Swedish land registry discloses the project status today as follows (Kairos Future, 2022):

> "The solution has not yet been subjected to scaling, optimization, and integration development."

All other projects are silent on the status of their projects or any timeline on going live. When so many crypto focused blockchain dApps are populating the rapidly transforming multi-trillion blockchain space, the total absence of non-crypto blockchain dApps points to nothing else than blockchain's commercial viability, particularly when a typical dApp development time averages around six months (Kalinin, 2021).

5.4 The real reason

An application that can be developed in six months (Kalinin, 2021) and we do not see anything in six years of active pursuit speaks volumes. The principal reason that real world non-crypto blockchain use cases have failed or stumbled is legacy blockchain's economic sustainability. As illustrated in Subsection 4.1, the cost of a blockchain transaction is unsustainably higher than a typical legacy transaction. It is not cost efficient to replicate transactions thousands of times (in case of proof of work blockchain) or at least about 20 times (in case of delegated proof of state blockchains), particularly when the transaction is a low value, low margin transaction, and the blockchain is Ethereum. Even if a minimum of five nodes (Androulaki et al., 2018) or ten nodes (Sousa et al., 2018), or up to 20 nodes (Nasir et al., 2018) that a private/permissioned blockchain network like Hyperledger or Corda deploys, the transaction data is replicated 5–20 times across the validating nodes with a downside that the permissioned blockchain offers no incentive to validating nodes. A high value transaction such as KYC valued at $13–130 (Jendruszak, 2022) that the Dubai blockchain project is now focusing on as a compromise, may be commercially viable, but a low value transaction, such as a consumer request for a copy of a government document, which normally costs not more than 25 cents, would be prohibitive if it was via blockchain.

That is not to say that there cannot be blockchain use cases or economically sustainable blockchains in future. In fact, there is already a successful non-crypto use case of blockchain operating since 2016 as a popular blockchain social network (BSN) platform – Steemit.com, that deploys Steem blockchain (Kim and Chung, 2018). Steem blockchain transaction costs are extremely low and the transactions it records on blockchain has an intrinsic value far higher than the transaction costs, leaving some surplus value that can be redistributed among the participating peers. But Steem-powered BSN is an exception, albeit a poster child of hope that there are possibilities beyond umpteen failures.

6 Scepticism, criticism and rebuttal

A vast plethora of scholarly articles hail blockchain as a powerful technology. It may indeed be. But so is nuclear tech. Do you use nuclear energy to heat up your morning cup of coffee? Do you use a cannon to knock down a fly? Everybody indeed has been talking about blockchain for quite some time now, but will it really change everything? And are the potential applications really endless?

In the face of the big blockchain hype, its criticism has picked up momentum (Song, 2019) and critics are calling it not only a crappy technology but a bad vision for the future (Stinchcombe, 2018). Schnier (2019), a renowned cryptographer and a public-interest technologist, whose wired opinion received industry-wide attention, asks a question and answers it:

> "Do you need a public blockchain? The answer is almost certainly no."

The outspoken economist, Nouriel Roubini (a.k.a. 'Dr. Doom' for predicting the last recession), called blockchain a 'big lie', and the most overhyped – and least useful – technology in human history (Roubini, 2018). Furthermore, Roubini claims Bitcoin/ Ethereum are more dictatorial and centralised than the rogue regime of North Korea.

If blockchain is a powerful technology, is it a solution looking for a problem? Majority businesses fail due to 'no market need'. Should we ask "does blockchain work?" or "does it work better than other technology solutions in the market?" What is the cost-benefit trade-off to switching to a new consensus-based technology solution?

Applying the transaction speeds and cost of Ethereum to all and sundry non-crypto applications that are being converted to dApps, the technology may indeed look crappy and useless. In fact, Ethereum should have no role in dApps of tomorrow. Ethereum does neither define the entire scope of the blockchain technology, nor it was designed to do anything more complex than jumpstart the ERC20 economy, which it undoubtedly did exceedingly well. Ethereum sure is a revolutionary milestone in the history of blockchain and deserves the top spot in the hall of fame. But the critics must realise two things:

1. Firstly, blockchain defines Ethereum, Ethereum does not define blockchain.
2. Secondly, Ethereum is the very first iteration of a smart contract and cannot limit the capabilities of the future iterations.

All the flaws of the first ever iteration of a blockchain smart contract cannot be automatically blamed on all the subsequent smart contract iterations to come. In the history of innovation, there is no evidence of a technology, the first iteration of which, could perform all the magic that the technology was eventually capable of in its more advanced iterations. It is like expecting second generation computers of 1960's to do the AI and quantum resistance of fifth generation computers of future (Figure 9). AI and centralisation resistance and cost efficiencies are still extraneous to the blockchains of current generation.

The transaction costs of current generation blockchains is not economically sustainable and their decentralisation is centralisation prone. Artificial intelligence (AI) has shown to improve decentralisation of blockchain-based decentralised autonomous organisation (DAO) (Xi et al., 2022) and improve cost efficiencies in blockchain processes (Wang et al., 2022). In our own quest for the optimal use cases for blockchain, we chose to first work on formulating a hypothesis that defines the problems, and then work on perfecting the inadequacies in blockchain. We gave ourselves the following due diligence criteria before embarking on a blockchain project:

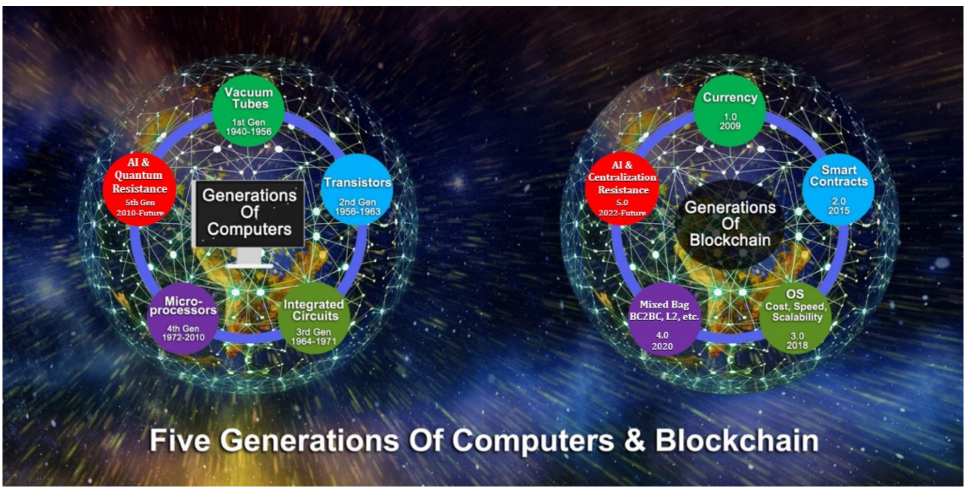
1 Whether tokenomics has a significant intrinsic role in the selected use case.

2 Whether decentralisation adds additional value over conventional low-cost relational database.

3 Whether value of each transaction (new data entry) is higher than the cost of recording it on the blockchain.

4 Whether there is incentive for peers to participate in the network.

Figure 9 Five generations of computers and blockchain (see online version for colours)



Source: AlgoShare (2018)

In designing the next generation blockchain that is economically and socially sustainable and in identifying appropriate commercially viable blockchain use cases, the following rules and key performing indicators (KPIs) will be helpful:

1 The transaction that the blockchain records should have significant intrinsic or perceived value to justify the cost of recording the transaction on the blockchain.

2 The cryptocurrency tokens that the blockchain generates to reward peer participation should have adequate liquidity in crypto exchanges.

3 The ROI or yield on a staked cryptocurrency token should be higher than the highest interest rate available in any legacy bank.

4 The cost of recording a transaction on the blockchain should be as close as possible to the cost of a traditional database and should leave a surplus value after covering all costs including staking investors' profits. Such surplus value ratio should always exceed 1 (reward value/total transaction cost) to make it a commercially viable solution.

5 Centralisation resistant consensus mechanism is crucial for a blockchain that is inclusive, equitable and non-discriminatory, and achieves a Gini coefficient of less than 0.5.

This review of state-of-the-art finds that above metrics are essential to implementing real world use cases, which are currently impossible to achieve with most blockchains out there, but certainly possible to custom design one with sustainability in mind. However, it should be noted that some of those KPIs can only be reached or proven only after the blockchain receives some traction in the marketplace.

At the 2018 World Economic Forum in Davos, 100% of the participants believed that even if the cryptocurrency bubble bursts, the token economy will prevail (World Economic Forum, 2018). The fact remains that the increasing amount of data and number of transactions will require new innovative systems that are economically, socially and environmentally sustainable. It might very well be that blockchain is not the right technology to revolutionise every use case conceived by the blockchain enthusiasts, but at least it will be a step in the right direction if the next generation blockchain development prioritises economic and social sustainability of its tokenomics model in select use cases.

7 Modelling the next generation blockchain

Zero carbon footprint, very low or zero transaction costs and public transparency are the fundamental qualifiers for a sustainable blockchain. While there may be a few promising blockchains, Steem is perhaps the only sustainable blockchain to our knowledge that has passed a full TRL 9 production grade maturity for a non-crypto use case such as BSN – Steemit.com. But Steem blockchain was not designed to implement smart contracts (Guidi, 2021).

Following are the three bare minimum requirements that a blockchain should pass to be considered as sustainable (Figure 10):

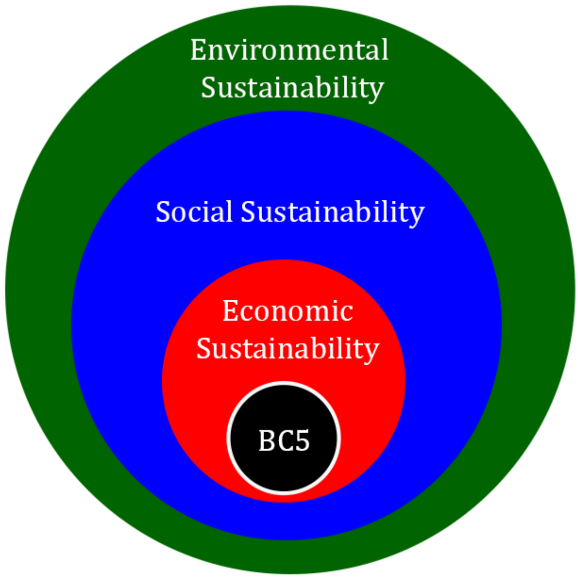
1 *Economically sustainable:* Transaction and data storage cost very low, or close to zero, or at least comparable to the cost of traditional relational databases. Economic sustainability is the absolute showstopper making social and environmental sustainability irrelevant.

2 *Socially sustainable:* Perfectly decentralised, equitable and inclusive and publicly transparent. This essentially means the blockchain's consensus mechanism is resistant to centralisation.

3 *Environmentally sustainable:* Almost zero carbon footprint.

As stated earlier economical sustainability has hardly been on the radar screen of blockchain researchers. Nevertheless, once in a while report purporting to be studying the economic sustainability dimension of blockchain emerge. Surprisingly a study purporting to be evaluating feasibility of blockchain for economically sustainable wireless mesh networks (Kabbinale et al., 2020), does not present any cost consequences of blockchain deployment in comparison to standard methods. Similarly, several papers report development of sustainable blockchain (Mattila et al., 2022) claiming novel (Shoker, 2017) consensus mechanisms (Li and He, 2020). However, without any empirical evidence that these blockchain projects will bring down the transaction costs and will be centralisation resistant, it is difficult how well they will endure the demands of sustainability.

Figure 10 Modelling the next generation sustainable blockchain (see online version for colours)



Just like TCP/IP, on which the internet was built, blockchain is a foundational technology that will require broad coordination which will take years before seeing any significant commercial traction. No wonder, despite years of hype, the blockchain industry has not seen any real-world use beyond its role in cryptocurrencies. The adoption of TCP/IP suggests blockchain will follow a predictable path that will take years to mature. It is time we got started with planning the next generation blockchain that models around economic, social, and environmental sustainability.

8 Limitation and caveats

The focus of this review is public blockchain essentially because the all-time high market cap of $3 trillion that can be attributed to blockchain comes exclusively from its cryptocurrency use case. Private or permissioned blockchains do not have any such capabilities and therefore their contribution to the existing blockchain economy is negligible. Furthermore, with IBM on the verge of exiting from the enterprise blockchain space (Gooding, 2022), the epicentre of the decentralised economy is public blockchain. As any hypothesis generating research demands, great care is warranted in interpreting the conclusions of this report for the following reasons:

1 The socio-economic hypothesis in this research is formulated based on empirical data from very limited published data as peer-reviewed publications on the economics and decentralisation dimensions of blockchain transactions is scarce.

2 Our research on blockchain pain points is ongoing and inferences drawn on the available data are preliminary and subject to updates as and when available.

3 This is hypothesis generating research that frames and supports a hypothesis based on available evidence. It does not claim to test and prove the hypothesis.

4 Rigorous investigations by peer researchers are needed for testing and proving or disproving the hypothesis framed and supported in this paper.

Despite its limitation this study adds compelling evidence that overcoming economic and social sustainability is not theoretically impossible if research focuses on reducing the transaction cost and increasing decentralisation.

9 Conclusions and future outlook

Blockchain is predicted to be a $3+ trillion business by 2030 (Horch et al., 2022), but it still has not achieved commercial viability beyond its success in enabling a thriving cryptocurrency industry. Great advances have been made in blockchain research in the preceding years, but the barriers to mainstream adoption beyond its cryptocurrency use, still stand tall. As they say complacency is death of innovation and accurate diagnosis is the only way to cure a disease, we cannot afford to remain complacent anymore. As cryptocurrency thrives and blockchain struggles to find its place, we need to reach an accurate diagnosis of what's ailing. This paper strives to do that. The worst part is that the barriers to mainstreaming of blockchain are not even fully defined. This paper tries defining the most lethal, but much ignored of those barriers. The existing blockchain platforms make it difficult or downright impossible to develop even simple on-chain dApps that can deliver real value outside of tokens and tokenised collectibles. Blockchain's very high transaction cost and its vulnerability to centralisation limits its potential.

Although UN SDGs cover a wide range of sustainability parameters, environment/ climate change has almost become synonymous with sustainability. Perhaps that is the reason almost all research on blockchain sustainability pertains to environmental sustainability. First and foremost, any technology must be economically sustainable, only then the question of environmental and social sustainability arises. It is time we looked for a sustainable blockchain that first establishes economic sustainability before validating its social and environmental sustainability.

Having discussed at stretch what the next generation blockchain should look like, it is opportune to answer some of the tough questions posed by the critics:

> "Will blockchain really change everything?"
>
> "Conservatively speaking, maybe not."
>
> "Are the potential blockchain applications really endless?"
>
> "Certainly not, at least not in the very near future."

Finally, the efforts made to write this article will be worth it if the critics who think blockchain is crappy, useless and a lie, may mellow down a little bit, and give the more advanced future iterations of this tech a chance with at least a select few specialised non-crypto use cases. It is not fair, if the critics and blockchain evangelists are expecting the current generation iterations of this technology to deliver the world. It will also be gratifying if this review of blockchain's sustainability spurs scholars into advancing blockchain research into the next generation. Time will tell if the future iterations of blockchain will deliver the magic.

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