Proof of Stake Blockchain Efficiency Framework

Algorand, efficient self-sustaining blockchain

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Abstract: “PERMISSION-LESS” IS NOT “RESPONSIBILITY-LESS”

On Earth Day 2021, in this article, we took the opportunity to show to the whole community why **Algorand does not trade sustainability for security, for scalability nor for decentralization**. Today we present a new framework of comparison for blockchain efficiency and sustainability that properly weighs these three essential elements of the blockchain’s purpose into the resulting score.

Sustainable development is a moral duty of our generation. As Algorand we believe that, in this historical and ecological moment, on planet Earth there can no longer be innovation without sustainability.

We believe that true commitment to a sustainable future is a collective responsibility: no single individual would ever be able to take care of our planet on their own, either we succeed together as species or we fail.

Decentralization and openness are foundational values for Algorand: these values, in fact, do not only shape Algorand’s evolution as an open and permissionless technology but also Algorand’s collective behavior as an open and inclusive community.

Being “*permission-less*” doesn't mean being “*responsibility-less*”. Algorand will never hide its own collective moral responsibility behind the “permissionless” excuses, all the opposite: at Algorand we think that the great challenge of coordinating an open and permissionless community represents an opportunity to decentralize and coordinate hard and difficult responsible choices, as earthlings.

BLOCKCHAIN SUSTAINABILITY METRICS

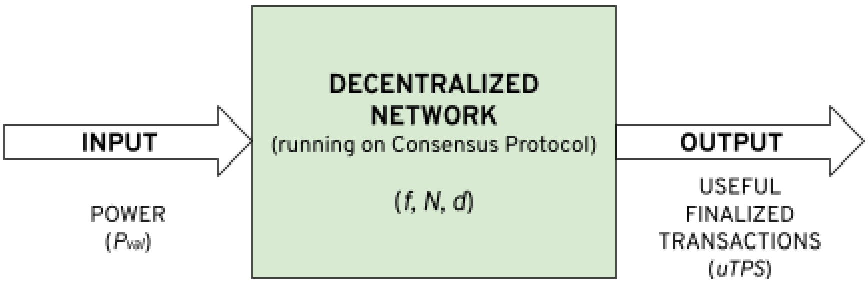
The debate on blockchain technology sustainability is gaining more and more relevance among communities, businesses, institutions and policy makers. As Algorand, we want to help keep such discussions as informative and transparent as possible, supporting the evaluation of blockchain sustainability, as a whole, with clear, objective and fair considerations.

First: if a study on blockchains’ sustainability does not take **decentralization** into account, then that study is discounting the primary function of a blockchain. Any centralized data-base technology, in fact, could be considered “sustainable” to some extent, but it is simply not a blockchain. As we stated in our previous article: *“Consensus Protocols such as Delegated PoS could easily claim, for example, that a network of 21 validators has low energy consumption, which is right, but the real challenge is being able to achieve sustainability without trading it for decentralization!”*.

Second: as with any other engineering process, blockchains' energy efficiency should be considered against "useful work". When we ask *"is this machine efficient?"* we are implicitly asking *"is this machine good at consuming input resources to produce the desired output for which it has been designed for?"*. This is true for motors, computers, rockets and… blockchains too. That's why it is fundamental to clarify that any evaluation on blockchains' sustainability should take into account the **power consumption used just for end user useful, finalized transactions**. By **end user useful transactions** ($uTPS$), we mean real users' transactions, excluding those one "consumed" by the Consensus Protocol functioning itself (if any). By **finalized transactions**, we mean transactions validated and permanently committed on the "main chain" (not a probable soft-forked or not finalized one). As we stated previously in our first article: *"the whole amount of energy spent in validating transactions belonging to "orphan chains" is completely useless, moreover, all the energy wasted on these transactions must be spent again, until they end up being appended to the longest chain"*.

Third: network "**validation**" and network "**popularity**" should be treated differently. The network could be "**popular**" because many Observer Nodes are synched as network's end-points but the "**validation effort**", on which efficiency claims should be addressed, only accounts for the power consumption actually used for block proposal and validation. In other words: "**network efficiency**" depends only on **validation power** consumption. Although there could be a proportional dependency between "**actual used TPS**" and "**network popularity**", there is no technical dependency between "**theoretical rated end user useful TPS**" and "**network validation**". In other words "**network efficiency**" is not a function of "**network popularity**". In the scenario where "**popularity**" is comparable among blockchains ecosystems, power associated to "network popularity" could be considered the same across different blockchains at steady state, if Observer Nodes requirements are comparable. Under this assumption, although "**network popularity**" counts in "absolute terms", it cancels out in "differential terms" between different blockchains. Asymptotically the real differentiator on blockchains' efficiency is just the **validation power** consumption (P_{val}).

Therefore, the following study will model blockchain sustainability taking into account **validation power** (P_{val}), **finalization rate** (f), **number of nodes** (N), **decentralization rate** (d) and **end user useful transactions** ($uTPS$)



to evaluate different blockchain networks with respect to the following question:

Is this blockchain network efficient at consuming energy to finalize end user useful transactions in a secure, scalable and decentralized way?

DECENTRALIZED NETWORK FINALIZED EFFICIENCY

Finalization Rate (f)

We define the *Finalization Rate* (f) to take into account the probability of block finalization as:

$$f = \frac{1}{B_F\,(blocks\ to\ finality)}$$

meaning that a network must spend the energy of the validation of B_F blocks before being able to consider the transactions finalized.

As an example, for Bitcoin this parameter would be:

$$f = \frac{1}{6}$$

meaning that in Bitcoin's PoW the network must spend the energy of 6 blocks validation before considering transactions finalized.

Finalized Transaction Energy per Validator Node (e_F)

The *Finalized Transaction Energy per Validator Node* (e_f) defines the average amount of energy spent by a Validator Node, that uses the power P_n, to finalize a useful transaction:

$$e_F = \frac{P_n}{uTPS \cdot f} \quad [Wh/tx]$$

Network Energy per Finalized Transaction (E_F)

The *Network Energy per Finalized Transaction* (E_f) defines the average amount of energy spent by the whole network, made up of N Validator Nodes, to finalize a useful transaction:

$$E_F = e_F \cdot N = \frac{P_{val}}{uTPS \cdot f} \quad [Wh/tx]$$

Decentralization Rate (d)

Defining a *Decentralization Rate* (d) for a blockchain network is not simple: a precise and rigorous definition of such a metric could easily fit as subject of an academic research, which is not the intent of this work.

Therefore, we will rely on a more simplistic definition of *Decentralization Rate* for Proof of Stake blockchains. In order to reach a common understanding of what measuring decentralization means in this proposal, we should agree on some definitions.

To facilitate the presentation of our arguments for the definition of a *Decentralization Rate*, let's use an example that relies on the comparison between Decentralized Networks, running on Proof of Stake Consensus Protocols, and engines, exploring the concept of efficiency of a machine.

In 1842 the French physicist Nicolas Léonard Sadi Carnot discovered that the efficiency of any classical thermodynamic engine, that converts heat into work (or vice versa), must be lower than a theoretical upper bound represented by the efficiency of a purely ideal machine, named Carnot engine after him. Such a *"perfect"* engine is a purely theoretical construct and cannot be built in practice.

This is probably the most elegant and general result in classical physics, it implies that any system undergoing any kind of thermodynamic cycle can only tend to the efficiency of a Carnot engine operating under the same conditions, but will never reach it, no matter how cleverly that system has been designed.

In the same way we try here to define an equivalent of a “Carnot engine” for PoS consensus decentralization.

Does such a theoretical decentralization upper bound exist?

When should we say that a PoS consensus is completely decentralized?

We consider three different *factors of decentralization* that concur to define the *Decentralization Rate* (d) of PoS networks:

1. *Stake Decentralization* (d_S)
2. *Network Topology Decentralization* (d_T)
3. *Nodes Hardware Decentralization* (d_N)

We have to quantify each of these three factors as *bounded per-unit metrics* so that d can express *"how far"* we are with respect to the *“purely theoretical decentralization”*. The metric d can range from 0 (*completely centralized*) to 1 (*completely decentralized*):

$$d = d_S \cdot d_T \cdot d_N$$

Let's try first to define an ideal theoretical condition of decentralization for each of those three per-unit decentralization factors. Then, everything deviating from those conditions will make a PoS more real and far from platonic ideality.

Stake Decentralization (d_S)

Since in PoS the probability of being elected as block proposer or as validator is directly proportional to validators' stakes, the distribution of such stake into the ecosystem has a fundamental role on PoS decentralization.

We will say that the *“stake is completely decentralized” ($d_S = 1$)* if and only if:

1. All the stake in circulation is taking part to the PoS validation;
2. All the validators participating in PoS validation hold the same amount of stake;

Statement 1. essentially measures **stake participation rate** in PoS validation and could be easily quantified as:

$$p = \frac{validation\ stake}{circulating\ stake}$$

that can theoretically range from 0 (*no participation in PoS validation*) to 1 (*complete participation in PoS validation*).

Note that this factor should be corrected somehow for all those blockchains that work with Delegated Validation: *delegated stake*, in fact, is qualitatively *“less decentralized”* than a *“non-delegated stake”*. We leave the definition of a rigorous *“Delegation Rate”* to future works, **giving an advantage to all blockchains that work with DPoS**.

Statement 2. essentially measures validators' inequality. We adopt a well-known wealth inequality or concentration index from the Macroeconomics field: the *Herfindahl–Hirschman Index* (HHI), which is an indicator of concentration, used mainly to measure the degree of competition in a given market. It can theoretically range from 0 (*perfectly competitive market*) to 1 (*monopoly*), and it is defined as:

$$HHI = \sum_{i=1}^{N} s_i^2$$

where s_i is the market share of firm i in the total market S (or, in our case, the stake share of the validator i in the total validating stake S), and N is the number of firms (or, in our case, the total number of validators).

The HHI takes into account both the **stake distribution among the validators accounts** and the **absolute number of validators accounts**. This is accomplished by taking a summation of the square of each participant's stake percentage.

- *Example 1*: the largest validator holds 80% of the stake, the next 5 largest validators hold 2% each, the reminder is equally distributed among 10 validators:

$$HHI = 0.80^2 + 5 \times 0.02^2 + 10 \times 0.01^2 = 0.643$$

- *Example 2*: the 6 largest validators hold 15% of the stake each, the reminder is equally distributed among 10 validators:

$$HHI = 6 \times 0.15^2 + 10 \times 0.01^2 = 0.136$$

- *Example 3*: All the stake is equally distributed among 20 validators:

$$HHI = 20 \times 0.05^2 = 0.005$$

- *Example 4*: All the stake is equally distributed among 100 validators:

$$HHI = 100 \times 0.01^2 = 0.001$$

So we finally define the *Decentralization Rate* as:

$$d_S = p \cdot (1 - HHI)$$

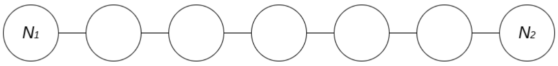
that can theoretically range from 0 (*complete stake centralization*) to 1 (*complete stake decentralization*).

Network Topology Decentralization (d_T)

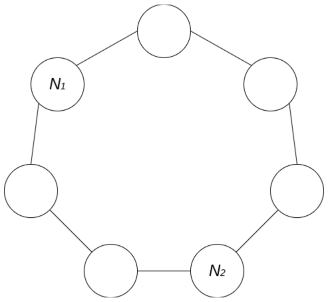
A blockchain is a public ledger of transactional data, distributed across multiple nodes in a network. All these nodes work together, using the same set of software and rules (the "Consensus Protocol"), to verify transactions that are then added to the finalized ledger. In order to keep the state of such a distributed system unique, coherent and synchronized the information must flow across the network, ensuring efficient paths of communication between the nodes. The message passing through the network can be achieved by routing the traffic on the network with different techniques. In Algorand, for example, information is spread across the network through *"message gossiping"* handled by the Relay Nodes, which route blocks to all connected nodes finding highly efficient communication paths and reducing communication hops.

Paths of communication are therefore essential to ensure that no one is excluded from the communication: everybody should be able to talk and listen to each other without relying on a few dominant paths. The more communication paths between nodes the more robust and decentralized the network.

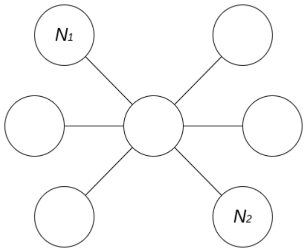
Let's try to visualize some communication paths examples between two generic nodes N_1 and N_2 connected through graphs that are intuitively different between each other:



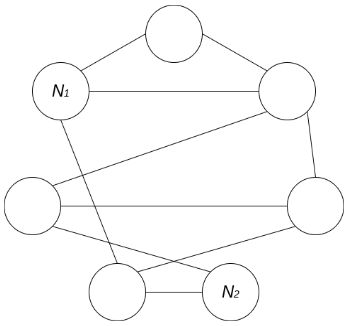
Network A



Network B



Network C



Network D

We can intuitively glimpse the difference between graphs A, B, C and D with respect to the concept of *“topology decentralization”*. Graph D is intuitively *“more decentralized”* than graph A, since it offers a larger set of communications paths between nodes N_1 and N_2.

Graph theory and network analysis define rigorous indicators of centrality, distribution and decentralization of a distributed system, assigning numbers or rankings to nodes within a graph corresponding to their network position. Networks in which traffic is obliged to pass through a few dominant nodes, for example, are less *“decentralized”* than networks in which the traffic is free to flow through several possible communication paths. Other metrics like *Betweenness Centrality* or *Closeness Centrality* are measures of centrality in a graph related to the evaluation of the shortest paths. One possible metric that fits well our requirements for *Network Topology Decentralization* (being a per-unit metric bounded between 0 and 1) is *Central Point Dominance*, which measures the maximum centrality of a node in a graph. This metric ranges from 0 to 1, where 0 represents a network in which there is no node such that all shortest paths have to pass through it, while 1 means all routes have to pass through that node. Network C in the examples above, for instance, is a graph with *Central Point Dominance* equal to *1*, since any message must pass through the central node to reach others.

For the scope of this paper we consider the same *Network Topology Decentralization* across all the blockchains ($d_T = 1$) , leaving the refinement of the calculation of this decentralization factor to future works.

Nodes Hardware Decentralization (d_N)

Another relevant factor to evaluate a network's decentralization is the rate of growth of the overall *“nodes’ hardware”* connected to the network. It is important to remark that this metric takes into account *“nodes’ growth rate”* rather than just *“nodes’ absolute number”*, for the following reason: one could easily say that 10 nodes are better than 1 node, or that 100 nodes are better than 10 nodes but, are 1.5 millions nodes really much better than 1 million nodes? What we are trying to state here is that the number of nodes should be analyzed as a growth phenomenon that tends to reach a steady state after which the addition of other nodes do not really impact decentralization in a linear and proportional way.

Sigmoid functions, like *Logistic function* or *Error function*, are a good way to model growth phenomena, their characteristic *"S"-shaped* curve perfectly models a system, like a network, that exhibits a progression from small beginnings, that accelerates and approaches a climax over time.

Cumulative Distribution functions, similarly, contain information on a phenomenon regarding its growth or distribution before or after a certain *“inflection point”*.

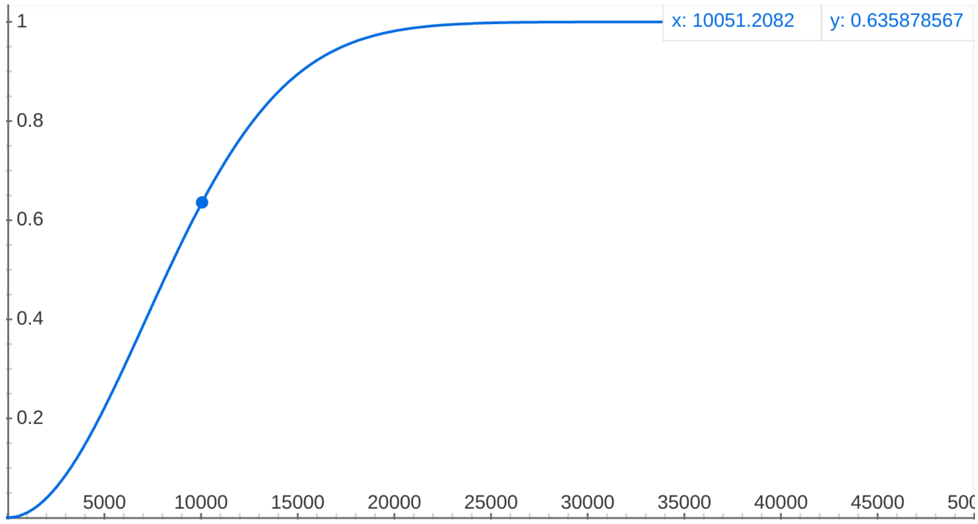
We propose to model the *Nodes Hardware Decentralization* as a *Cumulative Distribution*:

$$d_N = 1 - e^{-\left(\frac{N}{\lambda}\right)^k}$$

that can theoretically range from 0 (*no hardware growth*) to 1 (*complete hardware growth*).

The parameters k and λ should be calibrated to best fit the growth phenomenon with respect to an *“inflection point”*. The parameter k defines the speed of growth of the phenomenon. The parameter λ defines the order of magnitude of the inflection point for a given growth phenomenon. How to tune λ for a distributed blockchain network could be debated around the following question: *“what is the reasonable order of magnitude of nodes at which we can say that a network has grown sufficiently?”*. Our opinion is that a meaningful *“inflection point”* for a decentralized network should be greater than a few dozens or a few hundreds nodes, in particular, given the context of the analysis, we think adequate and reasonable to set: $k = 2$ for the speed of growth and $\lambda = 10^4$ for the inflection point magnitude:

$$d_N = 1 - e^{-\left(\frac{N}{10^4}\right)^2}$$



Decentralized Network Finalized Efficiency Score

The *Decentralized Network Finalized Efficiency Score* $(DNFES)$ is an **indicator** of the **overall efficiency** with which a decentralized network accomplishes its design purpose: finalizing end-user useful transactions.

$$DNFES = \frac{d}{E_F}$$

The higher the *Decentralization Rate* (d) and the lower the *Network Energy per Finalized Transaction* (E_F), the higher is the *Decentralized Network Finalized Efficiency Score*.

ALGORAND NETWORK ENERGY MODEL HYPOTHESIS

Algorand’s ecosystem and network evolved enormously over the last year, as a consequence we think that a refinement of Algorand’s energy model is necessary.

Moreover, during the year, other independent carbon footprint estimations have been proposed, in addition to our own hypotheses.

The refinement to our own personal estimation is based on some fundamental considerations derived from our original previous assumptions:

1. The number of **Relay Nodes** grown thanks to Community Relay Node Pilot programs;
2. Network "**usage**" and network "**capacity**" are conceptually different: variation on network "**actual used TPS**" marginally affects "**validation's power**" consumption. In other words: single Node's power consumption could be considered a constant all over the spectrum of "**theoretical rated end-user useful TPS**" ($uTPS$);
3. Relay Nodes minimum hardware requirements **can definitely not be sustained** by minimal hardware like a Raspberry Pi 4;
4. Validation Nodes minimum hardware requirements **can not be sustained** by minimal hardware like a Raspberry Pi 4 in high network usage conditions;
5. Observing Nodes minimum hardware requirements **can be sustained** by minimal hardware like a Raspberry Pi 4;
6. It is reasonable to assume that the power consumption of a Relay Node covers (and almost certainly exceeds) the power consumption of a Validation Node, so we can conservatively consider them equal.

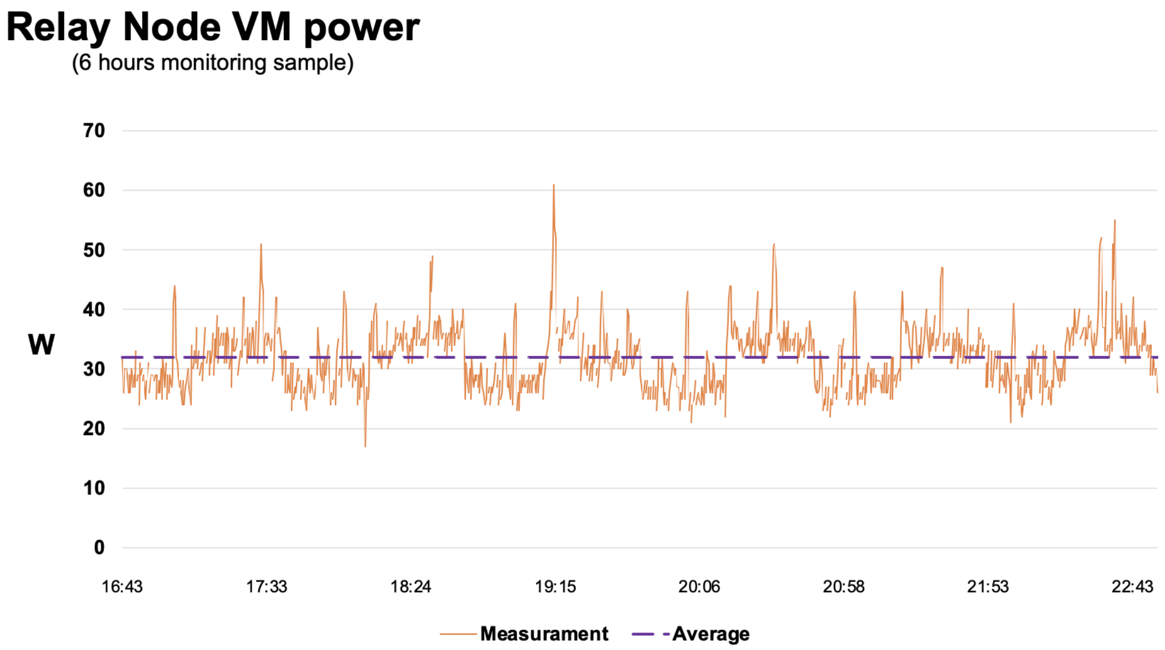
In addition to those observations we will take into account the following hypotheses, derived from the previous article:

1. Algorand PPoS keeps the same Relay Nodes and Validator Nodes hardware requirements regardless of the number of nodes participating in the consensus;
2. Algorand PPoS keeps the same "**theoretical rated end-user useful TPS**" ($uTPS$) regardless of the number of Validator Nodes (N_V) and Relay Nodes (N_R) in Algorand Network;
3. Relay Nodes and Validator Nodes process is accountable for the whole power consumption of the hosting hardware ($P_{n,V}$ and $P_{n,R}$ respectively), regardless of whether PPoS TPS are used at theoretical rated capacity or not;
4. Internet energy consumption has no differential impact between different consensus protocols;
5. Nodes Catchup and Storage power consumption is not taken into account;

ALGORAND VALIDATION POWER ESTIMATE

Given these qualitative observations we can now proceed to a more quantitative estimation.

Thanks to the *Cybersecurity Research Group of the University of Southampton* (member of the Community Relay Node Pilot program) we were able to perform a power consumption monitoring session, lasting 24 hours, on the virtual machine hosting a Relay Node.



As a result of the monitoring session we can reasonably affirm that a Relay Node consumes roughly 32 [W] on average. To take into account virtual machines power measurement's uncertainty, we introduced a rounding up of 25% on the power raw data, considering an overall average power consumption of 40 [W] per Relay Node.

Given all the aforementioned considerations, we end up obtaining the following metrics:

	Node Type	Node Power	Nodes Number	Total Category Power	Total Power
Network Validation (Val)	Relay	$P_{n,R} = 40\ [W]$	$N_R = 120$	$P_{t,R} = P_{n,R} \cdot N_R = 4800\ [W]$	$P_{Val} = 84800\ [W]$
	Validator	$P_{n,V} = 40\ [W]$	$N_V = 2000$	$P_{t,V} = P_{n,V} \cdot N_V = 80000\ [W]$	

**Algorand MainNet on March 2022*

As a matter of comparison with Proof of Work blockchains, according to the latest estimates, the equivalent for Bitcoin network is roughly $P_{val} = 16 \cdot 10^9\ [W]$.

ALGORAND FINALIZED TRANSACTION ENERGY PER VALIDATOR NODE

For Algorand, considering both Validator Nodes and Relay Nodes, we have:

$$e_{F,V} = \frac{P_{n,V}}{uTPS \cdot f} = 1.01 \cdot 10^{-5}\ [Wh/tx] \quad \text{and} \quad e_{F,R} = \frac{P_{n,R}}{uTPS \cdot f} = 1.01 \cdot 10^{-5}\ [Wh/tx]$$

ALGORAND NETWORK ENERGY PER FINALIZED TRANSACTION

For Algorand, considering both Validator Nodes and Relay Nodes, we have:

$$E_F = e_{F,V} \cdot N_V + e_{F,R} \cdot N_R = \frac{P_{t,V} + P_{t,R}}{uTPS \cdot f} = \frac{P_{val}}{uTPS \cdot f}$$

at the time of writing, for Algorand, the results is:

$$E_F = \frac{84800\ [W]}{1000\ [tx/s] \cdot 1} \cdot \frac{1}{3600} \frac{[Wh]}{[J]} = 0.021\ [Wh/tx]$$

ALGORAND FINALIZATION RATE

Thanks to **Pure Proof of Stake Instant Finality**, for Algorand we have:

$$f = 1$$

meaning that in Algorand’s PPoS the network only spends the energy of 1 block validation to consider transactions finalized.

ALGORAND DECENTRALIZATION RATE

Based on a snapshot of the Algorand blockchain on end March 2022, we have:

Stake Participation Rate (p)

$$p = \frac{validation\ stake}{circulating\ stake} = \frac{1.960 \cdot 10^9\ ALGO}{6.628 \cdot 10^9\ ALGO} = 0.296$$

Stake Herfindahl–Hirschman Index (HHI)

$$HHI = 0.028$$

Stake Decentralization (d_S)

$$d_S = p \cdot (1 - HHI) = 0.287$$

Nodes Hardware Decentralization (d_N)

$$d_N = 1 - e^{-\left(\frac{N}{10^4}\right)^2} = 0.044$$

Decentralization Rate (d)

$$d = d_S \cdot d_T \cdot d_N = 0.013$$

ALGORAND DECENTRALIZED NETWORK FINALIZED EFFICIENCY SCORE

We are finally able to calculate the Decentralized Network Finalized Efficiency Score for Algorand:

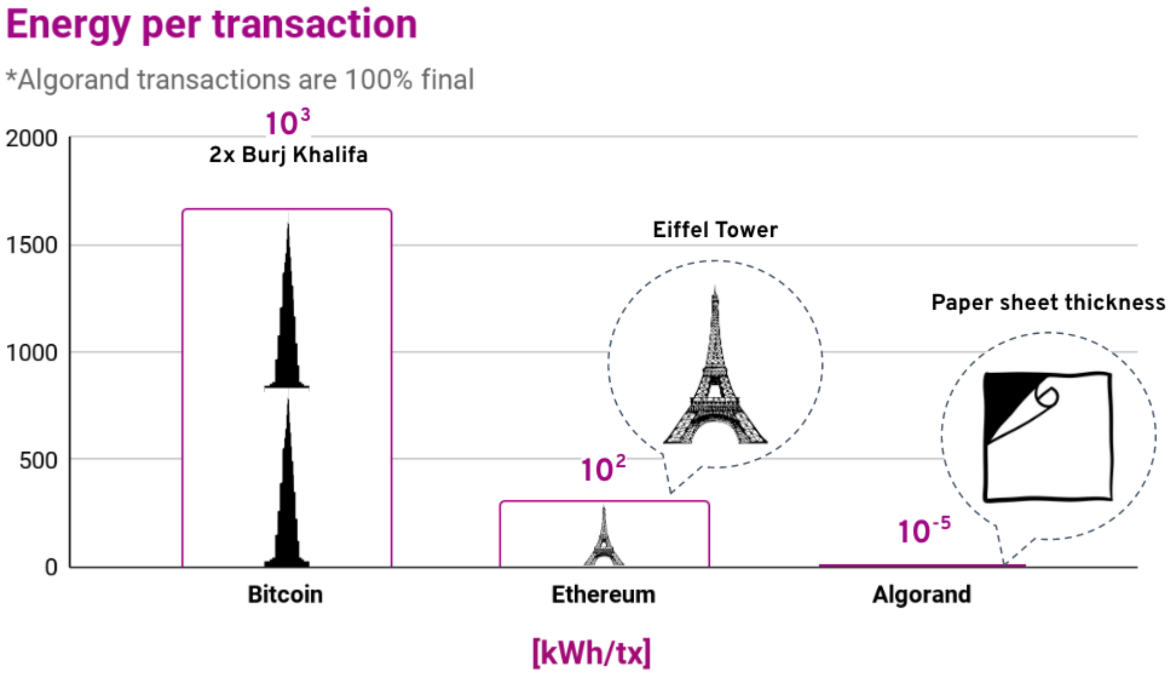
$$DNFES = \frac{d}{E_F} = 0.59$$

PROOF OF STAKE NETWORKS FINALIZED EFFICIENCY SCORE COMPARISON

Proof of Stake networks are orders of magnitude more efficient than Proof of Work networks, so comparing such different technologies on efficiency in the same framework is almost like comparing the efficiency of electrical motors to the efficiency of old internal combustion engines.

For sake of completeness let's summarize here a comparison between the energy per transaction in PoS (like Algorand) and in PoW (like Bitcoin and Ethereum):

- Bitcoin: 1700 $[kWh/tx]$ (non final)
- Ethereum: 290 $[kWh/tx]$ (non final)
- Algorand: 0.000021 $[kWh/tx]$ (instantly final)



The energy consumption difference between PoS and PoW is so huge that a single comparison framework between those technologies is not even justified.

Conclusion

The following table compares different PoS blockchains within the proposed sustainability framework. In order to evaluate sustainability metrics, specific for each blockchains, different kinds of data are required:

1. Data like *circulating supply* or *number of nodes* could be found on common chain explorers.
2. For nodes' power consumption of other blockchains we considered the third party estimation made by *"Energy efficiency and carbon emissions of PoS Networks" - CCRI Report - 2022*, while we relied on the power measurement conducted by the *Cybersecurity Research Group of the University of Southampton* for Algorand's nodes.
3. Data like *stake distribution, stake delegation rate* or *network topology*, require deep knowledge and specific understanding of each blockchain architecture. A precise evaluation of this category of data requires dedicated study and research, for each blockchain. Such an effort is behind the scopes of this first proposal.

Therefore we adopted a conservative and fair approach with respect to other blockchains in this comparison: for all those data that required extensive and specific research we considered the best possible value for the Validation Stake and its distribution (e.g. $HHI = 0$, *perfectly distributed stake*, which is much less true for those blockchain based on Stake Delegation), **giving to other blockchains an advantage on decentralization rate**, since a precise estimation of metrics like stake HHI would be out of scope for the present work. Decentralization rate should additionally be corrected for all those blockchains that work with Delegated Validation: *delegated stake*, in fact, is qualitatively *"less decentralized"* than a *"non-delegated stake"*. We leave the definition of a rigorous *"Delegation Rate"* to future works, **giving even more advantage to all blockchains that work with DPoS**.

We encourage all the compared blockchain to give evidence of more specific data about their performance Delegation Rate and Validation Stake characteristics.

	Algorand	**Solana**	**Cardano**	**Polkadot**	**Tezos**
Theoretical TPS $TPS\ [tx/s]$	*1,100*	*65,000*	*250*	*1,000*	*40*
End-User Useful Transactions $[\%]$	*100%*	*40%*	*100%*	*100%*	*100%*
End-User Useful TPS $uTPS\ [tx/s]$	*1,100*	*26,000*	*250*	*1,000*	*40*
Blocks to Finality $B_f\ [-]$	*1*	*32*	*6*	*10*	*2*
Finalization Rate $f\ [-]$	*1.000*	*0.031*	*0.167*	*0.100*	*0.500*
Validation Node Power $P_n\ [W]$	*40.0*	*221.3*	*22.8*	*27.0*	*34.5*

Finalized Transaction Energy per Validator Node $e_F\ [Wh/tx]$	*1.01E-05*	*7.57E-05*	*15.18E-05*	*7,50E-05*	*47.88E-05*
Validation Nodes $N\ [-]$	*2,120*	*1,625*	*3,000*	*297*	*375*
Network Validation Power $P_{val}\ [W]$	*84,800.0*	*359,661.3*	*68,310.0*	*8,019.0*	*12,926.3*
Network Energy per Finalized Transaction $E_F\ [Wh/tx]$	*0.021*	*0.123*	*0.455*	*0.022*	*0.180*
Circulating Stake $[-]$	*6.628E+09*	*0.518E+09*	*34.021E+09*	*0.988E+09*	*0.888E+09*
Validation Stake * $[-]$	*1.960E+09*	*0.390E+09*	*24.569E+09*	*0.713E+09*	*0.666E+09*
Stake Participation Rate * $p\ [-]$	*0.296*	*0.753**	*0.722**	*0.722**	*0.750**
Delegated Validation	*NO*	*YES*	*YES*	*YES*	*YES*
Stake Herfindahl–Hirschman Index * $HHI\ [-]$	*0.028*	*	*	*	*
Stake Decentralization * $d_S\ [-]$	*0.287*	*0.753**	*0.722**	*0.722**	*0.750**
Network Topology Decentralization $d_T\ [-]$	*1.000*	*1.000*	*1.000*	*1.000*	*1.000*
Network Hardware Decentralization $d_N\ [-]$	*0.044*	*0.026*	*0.086*	*0.001*	*0.001*
Decentralized Network Finalized Efficiency Score $DNFES$	***0.59***	***0.16***	***0.14***	***0.03***	***0.01***

** We kept the comparison conservative by giving to other blockchains an advantage on decentralization rate, since a precise estimation of metrics like validation stake, delegation rate and HHI would be out of scope for this work.*

NOTE

This study will be submitted to the *Journal of Alternative Investments* for formal review by an independent third party.

ALGORAND: A PERMISSIONLESS *SELF-SUSTAINED* BLOCKCHAIN

Given the Algorand network energy model presented, it is possible to estimate the annual carbon footprint of the network.

The estimation of blockchains' carbon footprint, in general, strictly depends on the energy generation matrix and the degree of renewables sources in the power grids that supply each node. In permissionless blockchain networks there is no way to predict where and how a given node is connected to the power grid, so the estimation of the carbon footprint has to rely on statistics about the emission intensity per kilowatt-hour.

Considering an average carbon intensity of $0.4\,[kgCO_2/kWh]$, Algorand presents a tiny annual carbon footprint of roughly 300 tonnes of CO_2 per year. For context, the equivalent metric for Bitcoin is 115,000,000 tonnes of of CO_2 per year.

This Earth Day 2022, Algorand Foundation is leaning further into its commitment to sustainability by pledging to permanently ensure the Algorand network is carbon negative and enforcing that pledge rigorously and transparently with protocol-level commitments on chain. Using native smart contracts, Algorand's minimal carbon footprint will be offset in perpetuity by the transaction fees of the network. The Carbon Negative Algorand (CNA) Smart Contract will use oracles to estimate current network performance and automatically purchase appropriate carbon offsets. The smart contract will fund those offset purchases from the Algorand transaction fee wallet. As the network grows, the transaction fees will grow and the network will always have the resources required to purchase the necessary offset. The CNA Smart Contract will run in perpetuity, ensuring that the Algorand blockchain will remain carbon negative forever.

We invite/challenge dApps built in our ecosystem to follow our lead and similarly commit their carbon footprint and offsets on chain making Algorand not only the first carbon-negative Layer-1 blockchain but the first carbon-negative blockchain ecosystem.