SoK Token economics of Web3 infrastructure networks - Part I: emission schedules

Christopher Heymann (1kx Network), Robert Koschig (1kx Network)

Updated June 20, 2023

Abstract

Converted into dollar values, Web3 infrastructure networks have emitted over $ 10 billion in rewards over the past years. Web3 infrastructure networks are decentralized networks of nodes providing hardware resources for a wide range of use cases like compute, storage, wireless networks or data indexing. In a series of articles we aim to understand how these networks design their policies and mechanisms around the economics of their flywheels, i.e. the incentivization of supply needed to attract usage and adoption which will eventually lead to the generation of income for the network helping then to further scale the supply and the network as a whole. Token rewards are a crucial part of the incentivization, which is why we start this first part of the series by describing the roles of the supply-side for Web3 infrastructure networks, their compensation mechanisms and presenting a classification of the token reward emission designs. We conduct an empirical analysis of the token rewards emitted by a representative sample of Web3 infrastructure networks that gained traction and present our findings. This sets the stage for further research around effective designs of the economics of Web3 infrastructure network.

1 Introduction

To fully realize the potential of Web3, robust decentralized infrastructure to support and enable the ecosystem is critical and as the space continues to grow, so has interest and usage in these underlying infrastructure networks. As monitored by the Web3 Index [1], which tracks key demand-side metrics for networks across the Web3 stack, and Messari's analysis of what they refer to as the DePIN (Decentralized Physical Infrastructure networks, [2]) sector, traction across these networks has greatly increased in recent months:

- Pocket network consistently above one billion relays per day ([3])
- Arweave transaction count at all-time high [4]
- Filecoin reaches record quality adjusted capacity [5] and launched the FVM [6]
- Helium has close to one million hotspots [7] and secured a partnership with T-Mobile [8]
- The Graph reached all-time high in paid queries [9]

A large driver of that traction are the rewards that are paid out to the participants of these networks to incentivize the supply side (e.g. storage, compute) of these networks: Converted into dollar values, the Web3 infrastructure networks we analysed have emitted over $ 10 billion in rewards over the past years. Yet, little research is available attempting to systemize and analyse the different approaches to inventivize the supply side of Web3 infrastructure networks.
We consider Web3 infrastructure networks as **networks in which a decentralized network of nodes provides hardware resources for use cases requiring such, e.g. compute, storage, wireless networks, bandwidth, message routing, data indexing or access control.**

We will go into more detail on this definition in section 3, explain its common components and lay out how we selected our representative sample for the subsequent analysis. Before, we briefly survey existing research related to the topic in section 2.

Section 4 discusses how the selected networks approach the incentivization of their supply side and how we classified those. In section 5 we present our analysis of the empirical data around reward emissions. One key finding was that despite the different design approaches, token emissions follow quite similar patterns:

- Relative to the total maximum supply of tokens, monthly emissions range from 0.2% to 1.2% in the first two years and then decrease to 0.7% and below afterwards
- Hence, typically less than 15% of the total token supply is spent for incentivization of the supply-side in the first year, less than 25% after two years and less than 45% after four years
- Emissions peak in the first year with a few exceptions that do so slightly later or don't plan for peaking emissions
- The positive market conditions of 2021 heavily impacted the dollar-value of these emissions leading to very different trajectories of these emission schedules

In section 6 we conclude and share an outlook on further research that we plan to conduct in this area for coming parts of this series.

2 Related research

Incentive designs for Web3 infrastructure networks is an area that is yet not well studied given it is rather small in a twofold sense: i) Incentive design itself is a small (yet important) component of the large, multi-disciplinary field of cryptoeconomic designs as laid out e.g. in [10] or [11] and ii) the market size of Web3 infrastructure networks is small, e.g. when using the DePIN definition provided by [12] it is roughly 0.5% of the total crpto market capitalization (as measured by [13]).

Hence, classifications of incentive mechanisms address wider areas like e.g. blockchain based systems as in [14]. This is also true for the various articles on the approaches to token and incentive designs, as provided e.g. in [15], [16] or [17]. The latter extends the introduction of the work token model and burn-and-mint model introduced by [18], which both are also widely used by Web3 infrastructure networks. [19] offers a model based analysis of the valuation of networks applying the burn-and-mint model and just recently extended this by the analysis on adequate compensation and incentivization of contributors also in the context of DePIN networks [20]. In contrast to our work it uses a mathematical description of those models and provides simulations around the expected dynamics. Similarly, [21] provide a relevant, yet model based description of the compounding of wealth and consequent centralization in Proof of stake cryptocurrencies. This is relevant to Web3 infrastructure networks given staking is a common component of their incentive designs.

Empirical research that we are aware of is focused on specific aspects of the design of token design or spans over a wider range of networks, or both as e.g. [22], [23] analyse the relationship of limiting the token supply to the token price for over 700 networks or [24] analysing vesting schedules and token distribution. Focused to Web3 infrasturcture networks, [25] used an Agent Based Simulation approach trained on data of Helium, Chainlink and Filecoin to analyse the impact of token emission scheme scenarios and user adoption on the token price.

[99] analysed the relationship of stake rate (the share of circulating supply staked) and token rewards for Arweave, Tezos, Livepeer and Irisnet to inform their token reward design of Nucypher[1]. Amongst other Web3 infrastructure networks that published analysis on their incentive design, NYM provides extensive game theoretic analysis and simulations around their reward sharing scheme that apply to stake mechanisms in general [65]. However, a description and systemization of compensation and inventivize mechanisms targeting the wide range of Web3 infrastructure networks is not available to date to our knowledge.

[1]The analysed timeseries data ($<$ 1 year) doesn't show strong signs that stakers decrease stake when rewards decrease, rather the opposite

3 Definitions

Web3 infrastructure networks. As mentioned in the introduction we define Web3 infrastructure networks as **networks in which a decentralized network of nodes provides hardware resources for use cases requiring such, e.g. compute, storage, wireless networks, bandwidth, message routing, data indexing or access control.** Whilst that definition includes a wide range of networks, those networks always comprise the same roles on the supply-side:

Service nodes: provide the actual resource e.g. storage, compute etc.

Validators: form consensus about the fulfillment of services provided by other node types of the network.

Delegators (optional): token holders that stake their tokens with validators and/or service nodes

Gateway (optional): orchestrate the connection between users and service nodes

Supply-side describes the network participants that provide resources such that the network can fulfill its purpose, i.e. provide the service it is designed for to users of the network (who form the demand-side). These roles have different names and come in different forms for the different networks, which is why we summarized them for each of the networks we selected in tables 1 and 2 in the appendix A.
In order to limit the large set of Web3 infrastructure networks live today for our analysis, we i) followed established selections of such, e.g. as presented in the Web3 Index ([1]), ii) added networks that use tokens esp. for incentive rewards at least for nine months and iii) provide sufficient public information on the mechanics and empricial data of those. We see this list as starting point for extension in the future as the domain expands and matures. On the other hand it covers a diverse set for the identification of joint patterns and differences:

Storage: Arweave, Filecoin, Sia, Storj

Compute: Akash, Livepeer, Render

Data/message routing/mixing (incl. RPC): Hopr, Nym, Pocket,

Wireless network: Helium (LoRaWAN), Helium (5g), Pollen (5g)

Data access/indexing: Covalent, The Graph

Access Control: Nucyper

4 Approaches to incentivize supply

The main idea behind the incentivization of supply is simple: At inception, when there is little demand and/or willingness to pay for the network service, supply needs to be subsidized via incentives to overcome the chicken-egg problem of lacking demand because of insufficent supply. There are three sources to compensate the supply side:

i) **Share of network earnings/fees**: as the network earns revenue from users paying for the services, service nodes get a share (if not all)

ii) **Token rewards**: funds allocated/minted by the network to subsidize and incentivize the supply, often based on stake and paid in form of the network token

iii) **Other sources**: For example, endowments funded by i) and/or ii)

The different roles on the supply-side of our networks summarized in tables 1 and 2 are also incentivized differently. Table 1 shows the roles which rewards we want to analyse more closely. Dark and light blue are roles that are incentivized by the mechanisms we analysed, dark blue are the parts which we included into our empirical analysis, which is mainly the service nodes. We consider those the most interesting role given they provide the resources relevant to the specific network service.

Often, other roles are directly tied to service nodes or crucial to service node operations, which is why we added their parts of the incentive emisssions to the analysis: For Arweave and Filecoin service nodes also fulfill the role as validator. Similarly, for Helium the service nodes (hotspots) also fulfill the proof of coverage as validation. Pollen has those validators separated, but for consistency between the service areas we added them here as well. Hopr's mixnodes function mainly as service nodes of the network, but their (reward) payment is integrated into the validation that messages have been routed, see details on its proof of relay [61]. Mixnodes in NYM also fulfill such „partial“ validator role as they generate the measurement messages used to assess the quality of service (see details on the proof of mixing in section 6.4. [62])
The amount of tokens that delegates stake with service- or validator-nodes determines eligibility to provide services/work for all networks with such role: Livepeer, Akash, NYM, The Graph, Nucypher, Covalent and hence are added into the reward emission analysis for these networks.
Akash, Livepeer and Render incentivize the validators and delegates whilst service nodes are paid directly via fees from users, but e.g. on the Livepeer network Orchestrators typically also fulfill the service node role (transcoder) as this is the standard setup of the client [49][2]. Storj is paying STORJ token based on fixed dollar-amounts to service nodes and doesn't add rewards to our knowledge, which is why all cells in table 1 are blank.

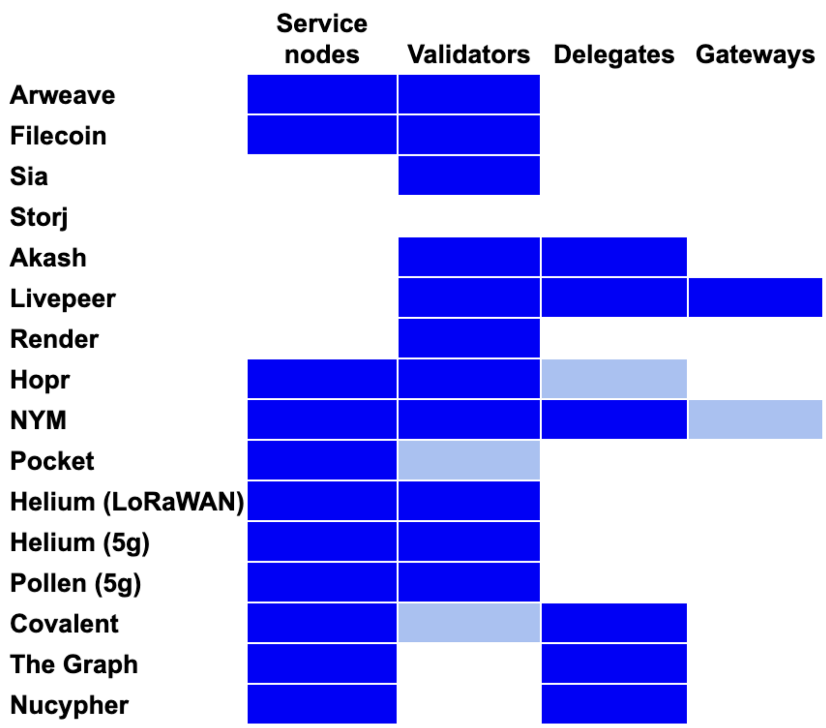

Figure 1: Dark and light blue cells are roles that are incentivized by the mechanisms we analysed. Dark blue are the roles which we included into our empirical analysis. See also the full overview of roles per network in tables 1 and 2.

The reward is available to the node operator after the work is validated, sometimes after a lock-up/vesting

[2]However, there are transcoders that are not Orchestrators contributing via pools, see e.g. [50]. Note also: whilst the Livepeer whitepaper [45] defines transcoders as fulfilling both the roles as service node and validators, current documentation [46] and onchain datasets (e.g. [47]) use Orchestrators to describe validators with transcoders as service nodes „under the hood“.

period (e.g. Filecoin). Typically, rewards can be claimed by the nodes, some networks facilitate their payments via probabilistic micro-payments though (e.g. Livepeer (when operated on Ethereum, [51]), Hopr [59]).

Token rewards are the source amongst the three presented above that networks can directly control by design, which is why we analyse these first. The share of earnings/fees are dependent on the demand, which is - even when incentivized as well - less direct. There are three aspects that determine the mechanics of the token rewards:

1. **Total token supply**
   - **Limited supply**: The maxiumum supply of native tokens is limited. Unless there is a burn-mechanism, the rewards the network can distribute to node operators is limited as well and hence will eventually diminish
   - **Unlimited supply**: The network has some sort of inflation mechanism that will continuously mint tokens without any set limit.
2. **Immutability**
   (a) **Adjustable**: Governance can vote to change the total token supply (1.) and/or the overall emission schedule (next point) - despite having the ability most networks didn't adjust their reward mechanisms to date (examples of those who did: Pocket[3], Helium[4], Akash[5] and Render[6])
   (b) **Not adjustable**: There is no governance or the token supply and emission schedule are out of scope of governance (e.g. Arweave, Sia, Storj)
3. **Emission schedule**: how much of supply is set aside for the supply side and how this is allocated over time

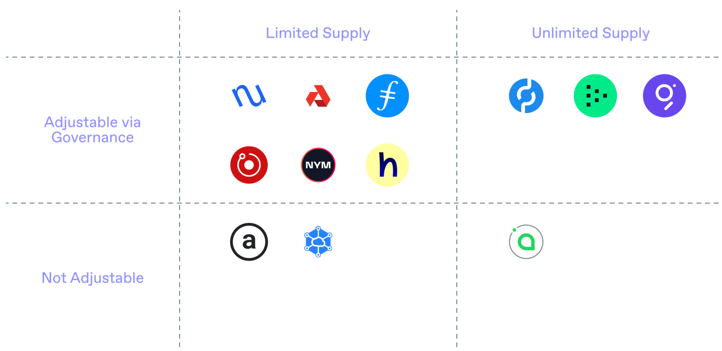

Figure 2: Icons of our selected Web3 infrastructure networks placed into the grid of their approach for token rewards with respect to immutability vs. total token supply

The design of the emission schedule offers greater complexity, which is why we discuss it in the following, separate section 4.1, where we will also discuss the relationship to the other two aspects.

[3]Pocket regularly revisits and adjusts their monetary policy and parameters, see e.g. [71]
[4]Helium changed the fundamentals of their mechanics early on: first to stop some participants gaming the incentives [75] and then to cap the total token supply[76]
[5]Akash regularly updates their inflation rates [43] and just started a discussion around updating their economics [44]
[6]Render just recently introduced governance and voted to switch to a burn-and-mint model [56]

4.1 Classification of emission schedules

Emission schedules are the function that defines the rate at which token incentives are distributed to node operators over time. This function has two dimensions:

1. **Complexity of the emission function:**
   - **Fixed**: the total rewards are only dependent on time (or current Blockheight b to be specific), i.e. rewards $R(b) = f(b)$ if f denotes the emission function
   - **KPI-driven**: additional KPIs (e.g. network capacity) impact the reward emissions: rewards $R(b) = f(b, KPI_1(b), \ldots, KPI_n(b))$. Note that this doesn't refer to the ability to adjust the schedules via governance we mentioned earlier.
2. **Shape of the emission function:**
   - **Decaying**: emitted rewards are decreasing towards zero over time
   - **Constant**: emitted rewards follow a constant amount or rate

Each of our networks falls at least in one of the resulting four quadrants as shown in figure 3. The following sections on each of the quadrants describe in more detail how the selected networks chose to setup their token rewards.

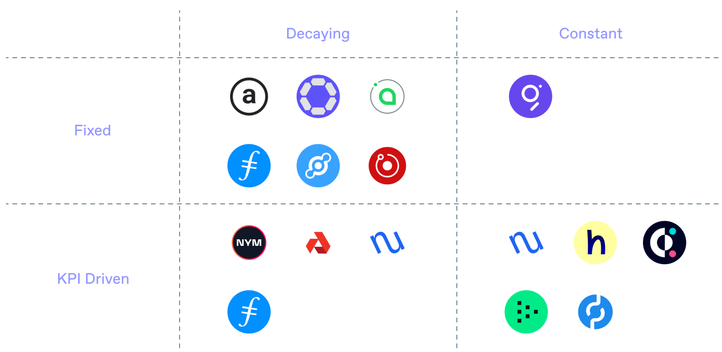

Figure 3: Icons of our selected Web3 infrastructure networks placed into the grid of their approach for their token rewards emission schedule with respect to complexity vs. shape of the emission function. Filecoin and Nucypher are represented twice as they have two components of their schedule falling into different quadrants[7].

4.1.1 Fixed and decaying emission schedule

Networks of this quadrant follow the example of Bitcoin, where token issuance and subsequent rewards for miners are reduced over time by a pre-set schedule. In the case of Bitcoin this means that every 210,000 Blocks (roughly four years) the BTC issuance rate halves. Most networks in this quadrant also follow such exponential decay, but typically with shorter „halving periods“, e.g. Helium (both LoRaWAN and 5g) rewards are planned to halve every two years and Arweave approximately one year as show in figure 4.

Example: Arweave

The Arweave blockchain is set to processes a block every two minutes, which means the estimated number of blocks per year is $BPY = 365 * 24 * 30 = 262,800$ [26]. Using the genesis supply $G_{AR} = 55,000,000$ AR

[7]Storj isn't included as they don't emit rewards as mentioned in section 4

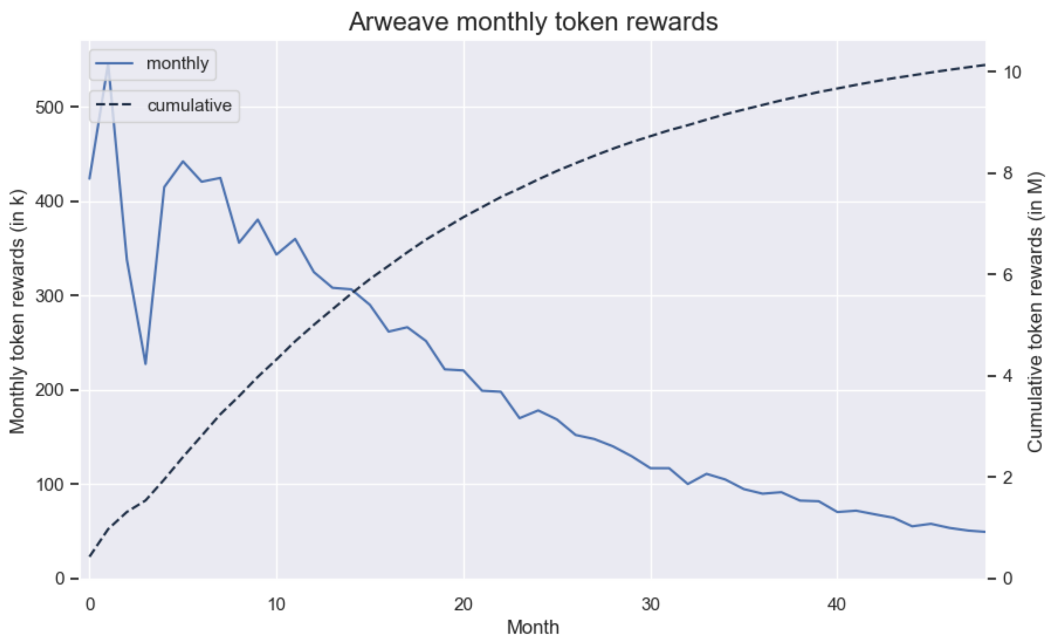

Figure 4: Arweave reduces the emissions of its AR token every block with a „halving“ roughly every year (every $BPY = 262,800$ Blocks), hence the exponential decay function of rewards and the convergence of the cumulative rewards to the total reward budget of 16.7% (11 million AR) of total supply (right axis)

the total token rewards at blockheight b is given by[8]:

$$R(b) = \frac{G_{AR} * 0.2 * \ln(2) * 2^{-\frac{b}{BPY}}}{BPY}$$

The other networks with fixed and decaying emissions are:

- **Filecoin** (simple minting, [35]): Filecoin has two ways to issue token rewards: the simple and the baseline minting. The former issues rewards every block following an exponential decay such that they halve every six years (the latter is covered in the next subsection).
- **Sia** [40]: started with emissions of 300,000 SIA per block (0.0067% of genesis supply), which were reduced by 1 coin each block until it hit the minimum emission of 30,000 SIA as blockreward in July 2020. These rewards are only paid to validators of the SIA blockchain, i.e. there are no token rewards for service nodes.
- **Render**: didn't have token rewards yet, but approved the switch to a burn-and-mint model similar to Helium's approach [57]. Additional 20% are planned to be minted to be distributed as incentives to node operators in a decaying fashion [58].
- **Helium (LoRaWAN)**: After the adjustments (mentioned in the examples for „Immutability“ on token rewards in 4), Helium halves the reward emissions every two years (starting with 2.2% of total supply (5 million HNT) per month). Hotspots (the service nodes) get a share of those that is set to change a couple of percentage points every year [77].
- **Helium (5g)**: started with daily reward emissions of 0.04% of total supply (100 million MOBILE), which will halve in August 2023 (after some adjustment in the course of the Solana migration) and

[8]Note: This version is from the code-source [30], whilst the formula presented in the yellowpaper [26] isn't correct/ has some typo.

then follow the Helium (LoRaWAN) schedule of halvings every two years (see [83] for details). Service nodes are allocated 60% of that [84].

- **Pollen** [87]: allocates 50% of the total token supply for reward emissions for service nodes, validators and users, starting with 2.1 million PCN per week and halving once this pool decreased by one third, which is after roughly 1.5 years and a second time around 3 years after that. The split amongst the user groups depends on their participation detailed out in [87].

4.1.2 KPI-driven and decaying emission schedule

Networks in this quadrant also apply an emission schedule that is decaying to zero. A KPI-driven schedule means that these emissions don't depend (only) on time/blockheight.

Example: Filecoin

As mentioned in the last subsection 4.1.1, Filecoin has a dual minting model: simple and baseline minting. The former allocates 30% and the baseline minting allocates the other 70% (770 million FIL) of a total reward budget of 1.1 billion FIL (55% of the total FIL supply).
Baseline minting emits rewards according to its KPI of an (increasing) target baseline of storage capacity (measured in raw-byte power) provided by the network: Whenever the actual storage capacity of the network ($R(t)$) exceeds the current target baseline ($b(t)$) the rewards are capped. The exact formula is ([36]):

$$\begin{aligned}
R_{\text{baseline}}(t, b(t)) &= R_{\infty \text{ baseline}} * (1 - \exp(-\lambda\theta(t, b(t)))) \\
\text{where } \theta(t, b(t)) &= \frac{1}{g} \ln\left(\frac{g\overline{R_\Sigma}(t, b(t))}{b_0} + 1\right) \text{ is the effective network time} \\
\overline{R_\Sigma}(t, b(t)) &= \int_0^t \min(b(t), R(t))\mathrm{d}x \text{ the cumualtive capped raw-byte power} \\
\text{and } b(t) &= b_0 \exp\left(g * t\right) \text{ the baseline function describing the target storage capacity at time } t
\end{aligned}$$

$R_{\infty \text{ baseline}}$ describes the total baseline minting allocation of 770 million FIL. λ, g and b_0 are parameters set by the network (see [37] for the exact values). The first equation shows that the function expresses a decaying structure, where rewards halve as well. In fact the simple minting uses the same decay factor λ which sets the rewards to halve approximately every six years. That decay is also visible in the actual emissions shown in figure 5.

The other networks with KPI-driven and decaying emissions are:

- **NYM**: allocated a pool of 25% of the total supply (250 million NYM) for mix-node rewards. Each 720 epochs (approximately one month) a maximum of 2% of that pool is emitted (hence decaying, as that is equivalent to halving rewards roughly every 2.8 years).
  However, the actual amount depends on the number of active nodes and their performance [64]. NYM also mentions that this reward pool is supposed to get refilled at a later stage with fees.

  The reward scheme to allocate the total rewards to individual nodes and delegates includes a reputation system, a parameter to impete sybil attacks and is the only one amongst our selection that asks nodes to pledge their cost [65]. Both game theoretic analysis and simulations [66] show that this promotes decentralization and performance of the network.

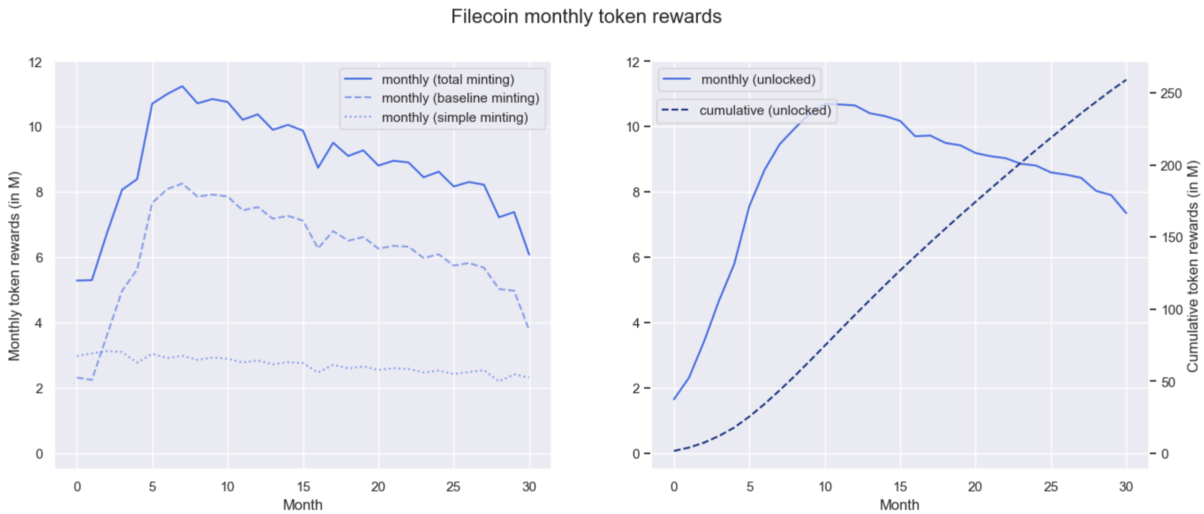

Figure 5: The left chart shows the total rewards minted (solid line) which is mainly impacted by the baseline minting (dashed line). The decaying nature is visible from month 6 (when the so-called Baseline crossing [38] happened: $R(t) > b(t)$) and onwards. The unlocked emissions (right chart) are shifted in time vs. the total rewards minted (left chart) as 25% of minted rewards are available immediately, 75% are unlocking over the subsequent 6 months.

- **Nucypher**: planned two phases of a KPI-driven schedule, with phase 1 having constant and phase 2 decaying emissions [99]:
  - Phase 1 planned constant emissions of approximately 25% of the maximum NU supply (roughly 1 billion NU) over roughly 5-8 years. This time range wasn't fixed upfront as as it depends on the share of circulating supply staked (stake rate) and the time stakers lock their stake
  - Phase 2 planned exponentially decaying rewards. The time for halving (approximately 2-4 years) depends on the stake rate and individual lock up times as well

  As mentioned in section 2 this approach was inspired by an analysis of staking behavior on other networks. More details on this mechanic are available in a comprehensive analysis by Gauntlet which also includes simulations around the WorkLock [100]: nodes could stake ETH in order to accumulate NU which provided a novel way to onboard new nodes. Also note: Nucypher merged with Keep protocol to Threshold Network at the end of 2021 [101].

- **Akash**: followed Nucypher's phase 2 in their Whitepaper [42], i.e. exponentially decaying rewards with the halving period depending on the stake rate and lock up times. Governance adjusted the halving period to 3.7 years early on and regularly adjusts the inflation targets [43].

4.1.3 Fixed and constant emission schedule

Constant emissions refer to a constant amount or rate of rewards that the network distributes, e.g. 200 tokens per day or 3% inflation each year. The important difference to previous quadrants presented is that emissions are not scheduled to decay to zero eventually. These constant emissions are only „flat“, i.e. constant over time if it is a constant amount that gets issued. If it is a constant rate, i.e. a fixed inflation, then the total supply grows and so does the issued amount as the following example shows.

Example: The Graph

A 3% annual inflation (based on the current supply of GRT) is allocated to GRT stakers, which includes delegators. This results in steadily increasing reward emissions as the total supply is also increasing. However as GRT rewards are claimed by Indexers the solid line representing these emissions over time in figure

6 does not reveal this trajectory. Rewards for Indexers are a share of those claimed rewards which they can set individually (see [94] for details on the split).

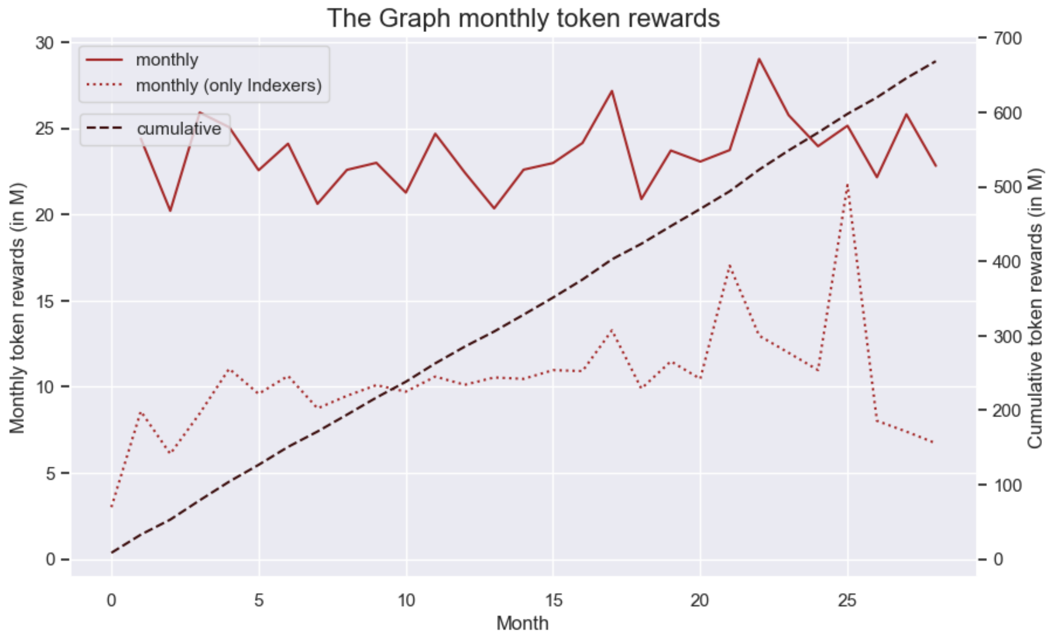

Figure 6: The solid line shows the emissions to Indexers and GRT stakers based on the 3% annual inflation (based on initial supply of 10 billion GRT), the dashed line (right axis) shows the cumulative sum of those. Indexers individually define the share of the rewards they keep shown as dotted line, and also the time when to claim, which results in less constant lines over time.

Amongst our set of networks there are no other examples of a fixed schedule with constant emissions.

4.1.4 KPI-driven and constant emission schedule

Constant emissions refer to a constant amount or rate over time (that is not decaying such that they approach zero). KPI-driven means that these emissions depend on some set KPI/variable and don't depend (only) on time.

Example: Livepeer

There is a fixed rate at which staking rewards are emitted each round (5760 blocks), therefore a constant emission. This rate increases (every round) though if less than 50% of all LPT supply is staked and conversely decreases when over 50% are staked. Therefore the actual emission is dependent on this stake rate and not on time. The result is a token emission that doesn't look very constant over time, only when the KPI (stake rate) is less volatile as visible in figure 7.

Example: Pocket

The Pocket Network uses a RelaysToToken Multiplier to determine how much POKT is minted each day (and consequently paid as reward) for each relay a node services. Some share of those rewards go to validators of the Pocket-chain and to the DAO, but 85% go to the service nodes[9]. As long as this multiplier stays the same this is a constant emission. It does not depend on time, but on relays serviced and hence the emissions follow a KPI-driven schedule, see figure 8.

[9] Changed from 89% via governance in June 2022 [72]

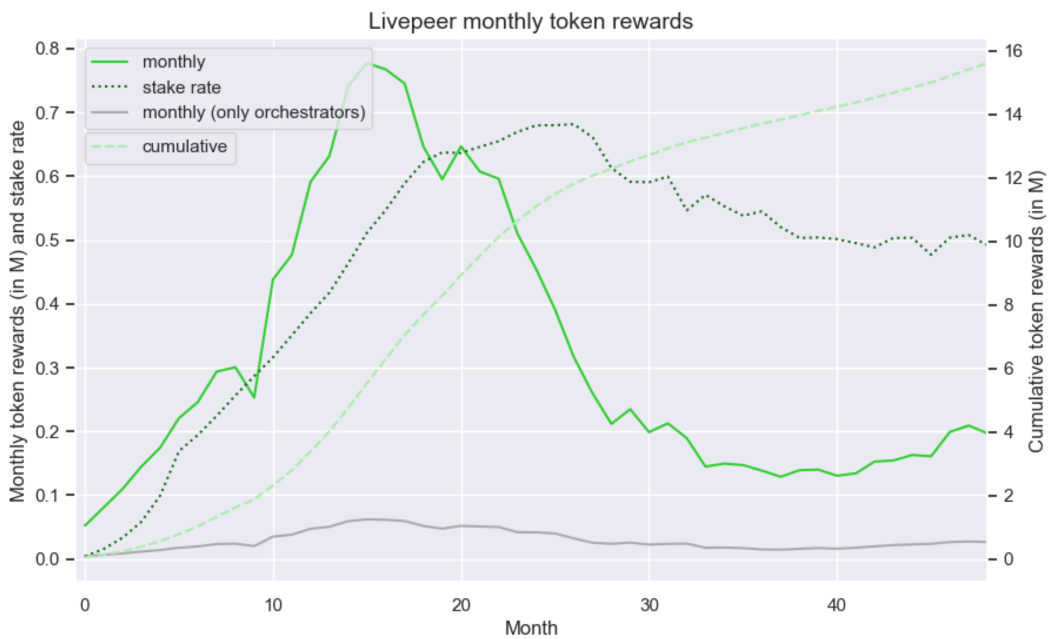

Figure 7: In the early months the stake rate (dotted line, left axis) is below 50% (0.5) such that the inflation and hence the monthly emissions increase (solid green line, left axis). Emissions for token rewards peaked when the stake rate crossed 50%. They decrease and stabilize in parallel to a stabilizing stake rate around 50% afterwards. Orchestrators (gray line) keep a cut of those rewards, typically 10-15%.

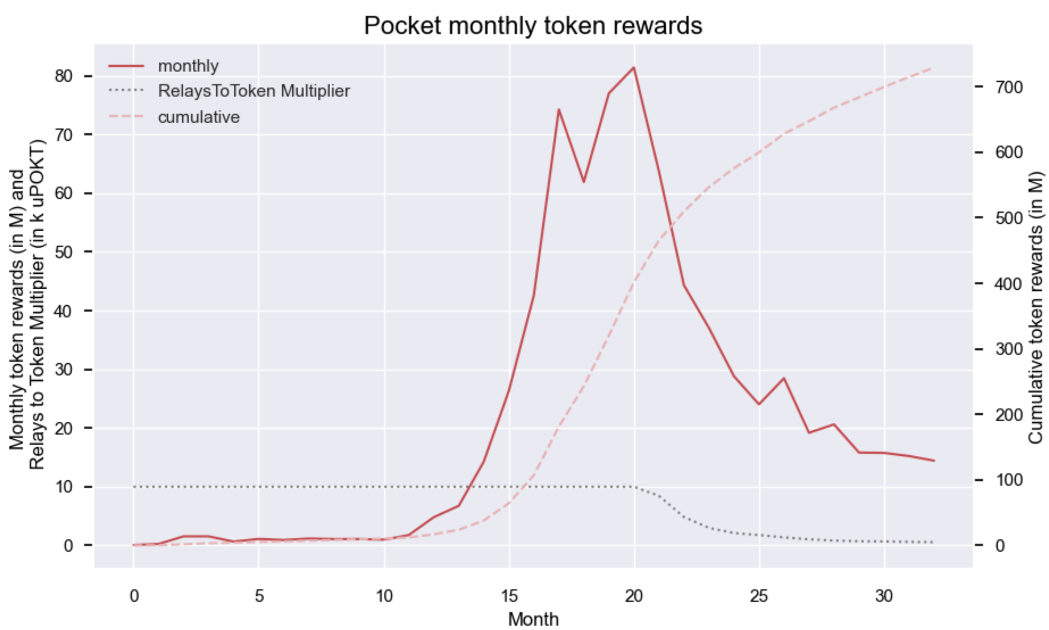

Figure 8: As the number of relays serviced per day saw a big increase in early 2022 (roughly 1.5 years after launch), so did the monthly POKT emission (solid line). As governance also adjusted the RelaysToToken Multiplier (gray dotted line, left axis) to manage the effective inflation, the resulting emission is not that constant after all.

The other networks with KPI-driven and decaying emissions are:

- **Hopr** [60]: follows a similar logic as NYM, but planned allocating a constant amount per month for cover traffic, the actual emissions being subject to network conditions and governance. The overall supply is still limited as those rewards are set to last only two years[10].
- **Covalent**: is about to announce more details on their node rewards soon, but an emission of constant amounts over time with a maximum of 2% of the total supply per year is planned. The actual amount depends on the amount and type of nodes that get rewarded. Currently, individual node operators (and their delegates) get a constant emission of CQT from the dedicated share based on the block specimen they produce [90].
- **Nucypher**: As mentioned in 4.1.2, phase 1 of Nucypher had constant emissions, yet the total time range for those are subject to the stake rate and hence monthly token rewards emitted are subject to that as well.

5 Aggregated empricial analysis

Whilst actual token rewards emitted by Web3 infrastructure networks with a fixed schedule should follow their planned schedule, we were interested in the patterns that emerge for KPI-driven schedules and more broadly how actual token rewards of the four quadrants and the individual networks compare to each other. We will do so by first, introducing the relative token emissions to make the amounts of token rewards emitted compareable across networks. Next, we will analyse how the token rewards translated into dollar-values using the historical price data of the respective token.
To provide an anchorpoint to put the presented values into perspective, we added the respective timeseries of miner reward emissions for Bitcoin and Ethereum. The sources used to derive the data for all networks are listed in table 3 in the appendix.

5.1 Relative emission schedules

To compare the emission schedules of the different networks we derived the relative emission schedule for each network by dividing token issuance with the maximum token supply the network aims to have. For networks with unlimited supply (SIA, Livepeer, Pocket, The Graph) we projected ten years with current (net) inflation to get an estimate for the maximum token supply for this indicative comparison. The aggregated view by quadrant is presented in figure 9.
Fixed and decaying schedules (blue) start their relative monthly rewards in the range of 0.7% - 1.7% of total token supply and decay to 0.2% - 1% after two years. KPI-driven and decaying schedules (green) follow a similar pattern but on lower ranges of 0.1% - 1.2% early on, decaying below 0.5% after two years[11] and having peak emissions a bit later than the networks with fixed-decaying schedules.

The ranges for KPI-driven, but constant emissions (yellow) is quite broad given Hopr and Covalent have quite low relative emissions (less than 0.1%), whilst Livepeer and Pocket ramp up over the first year and then show quick increases and decreases around their peaks around 15-19 months. Beyond year two emissions decay below levels of 0.7% , but don't approach zero (afterwards it only entails the timeseries for Livepeer).
For fixed, constant emission schedules (brown) we only have The Graph in our data set, which is at the lower end of the shown ranges as well.
Summarizing, decaying schedules start higher whilst KPI-driven schedules are reactive to market environments affecting the underlying KPIs and therefore are hard to compare.

[10] One could argue that hence Hopr follows a decaying schedule given the token rewards are set to be zero after two years.
[11] Note: As we rely on data of rewards actually paid, there is fewer data points for higher months, e.g. just Sia, Arweave and Livepeer paid rewards beyond month 50.

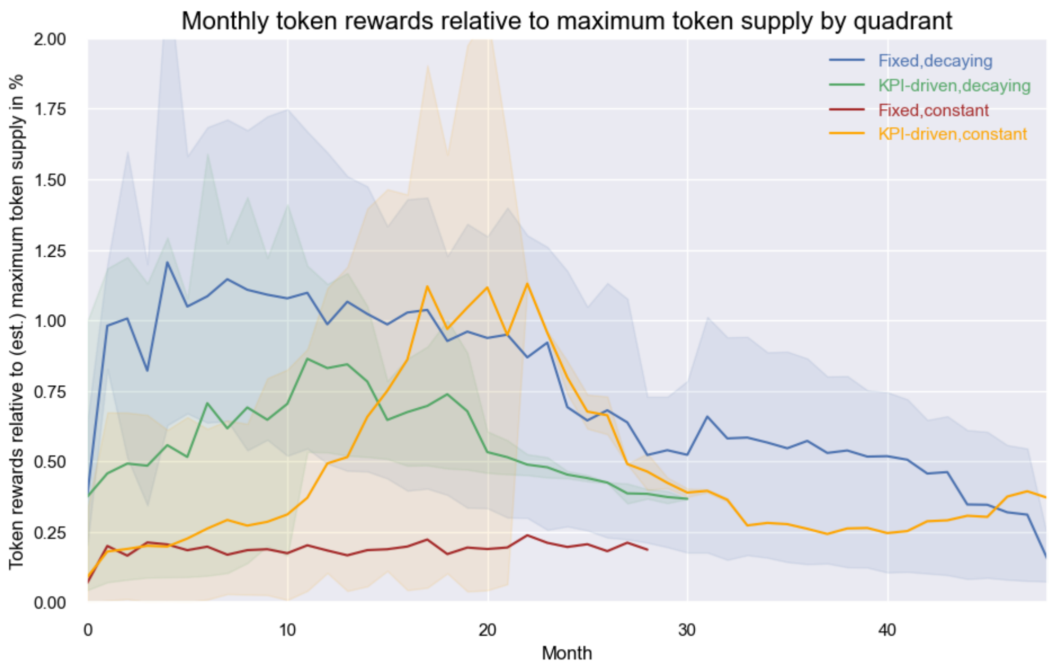

Figure 9: Monthly token emissions aggregated for each of the quadrants presented in 4.1. The solid line represents the average over all networks of each quadrant, the shaded regions are bound by minimum and maxiumum, respectively.

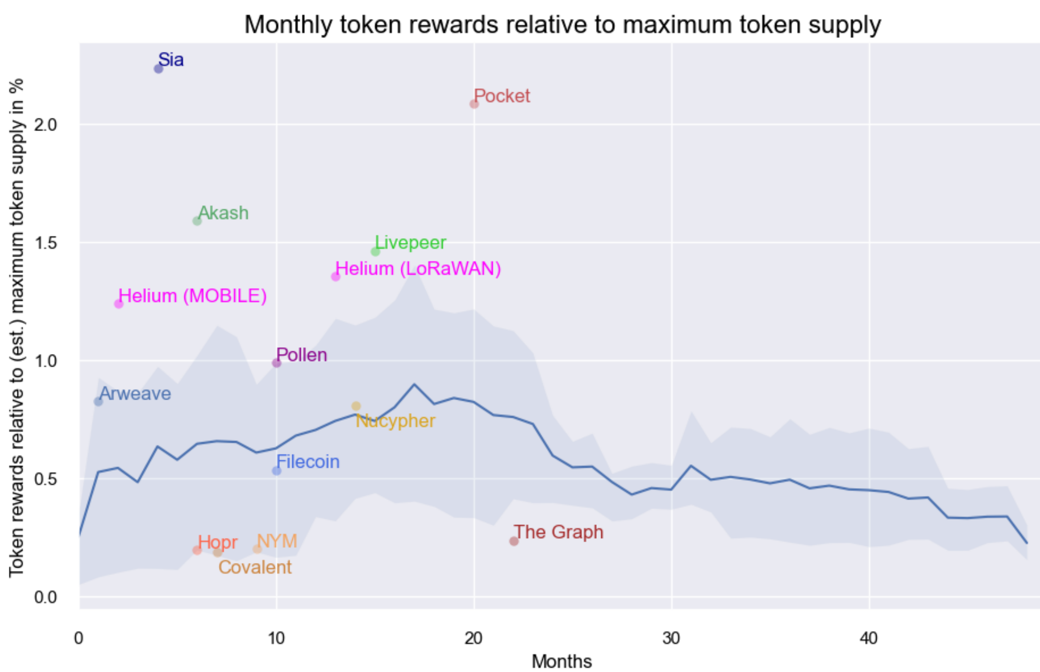

Figure 10: Average monthly token emission over all networks relative to their maximum token supply (solid line is the average, shaded is the interquartile-range of our data points). Colored points mark the peaks of monthly emissions (yet) for each network.

Acknowledging that we have nine networks with decaying and five with constant emission schedules, an aggregated view over all networks is presented in figure 10. To summarize what we have just observed on the ranges for the four quadrants seperately, the monthly issuances relative to the (estimated) maximum supply overall are in similar ranges: early on at around 0.1% to 1%, increasing to ranges of 0.4% to 1.4% and fading out at 0.7% and below after two years. Consequently, the peak of reward emissions is in the first year for most networks[12], Livepeer (around month 15) and Pocket (around month 19) - both in the KPI-driven, constant quadrant - are noteworthy exceptions.

5.2 Dollar-valued emission schedules

Figures 9 and 10 presented above show that token rewards of Web3 infrastructure networks are typically higher in the early stages. One goal of these rewards is to compensate for the investments that node operators made, which occur in fiat/dollars. When looking how the token emissions translate into „dollar-emission“ schedules, we see that they follow very different patterns, regardless which quadrant their approach fits into, as shown in figures 11 and 12.

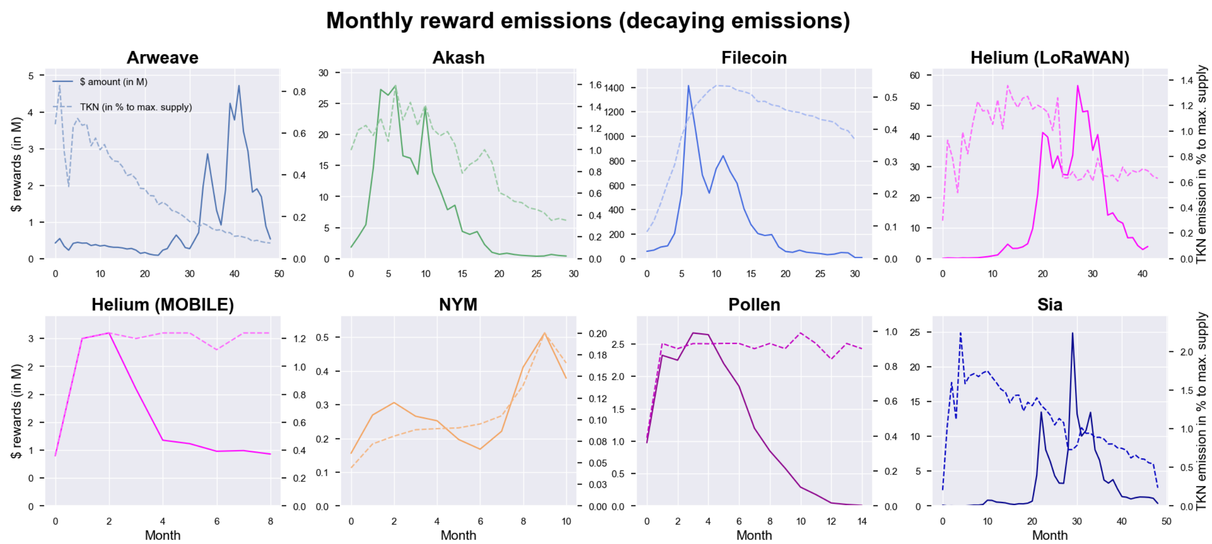

Figure 11: The monthly token rewards in for each network with decaying schedule[13] as dollar-values (solid line, left axis) and relative to the estimated maxiumum token supply (dashed, right axis)

All networks saw their peak dollar-emissions during the second half of 2021, which happened at different times of the networks' timeline. This explains why dashed and solid lines are so different in the charts of figures 11 and 12, e.g. Arweave's token rewards in dollar-terms peaked after month 40 when the monthly token rewards already decreased to levels below 20% of their peak, i.e. 0.1% of the total AR supply (upper left chart in figure 11).
It is interesting to observe that those monthly token rewards in dollar-terms peaked in the tens if not hundreds of millions of dollars. **Converting the emitted token rewards of our selected networks of their first two years, they add up to over 10 billion dollars.** It is worth noting though that Filecoin contributed over 85% of that total as the FIL price peak during 2021 and high token reward emissions coincided.
More recently launched networks like Helium MOBILE, Pollen and NYM have not experienced such positive market tailwinds yet. NYM also has lower monthly token emissions in general.

[12] The peak of The Graph is just one of the last data points available - per its schedule design it doesn't peak.
[13] Nucypher's decaying schedule for phase two of their emissions isn't included as this phase has never been activated due to the merger into Threshold protocol before [101], Note also: Helium MOBILE, Pollen and NYM haven't seen their emission reductions yet, hence no decline in the dashed lines yet.

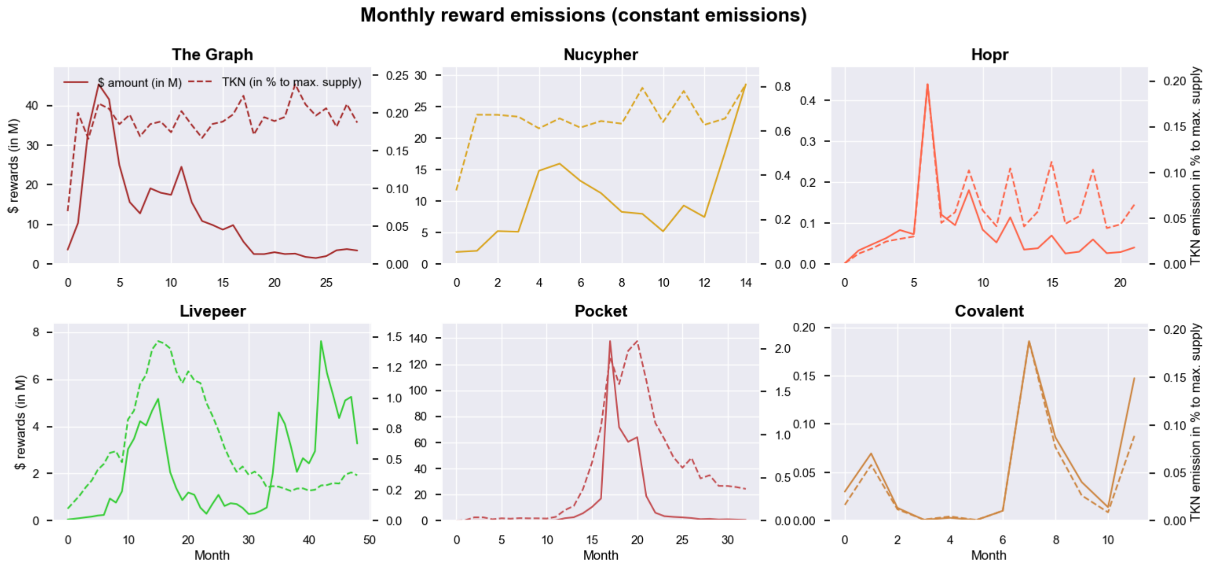

Figure 12: The monthly token rewards in for each network with constant schedule as dollar-values (solid line, left axis) and relative to the estimated maxiumum token supply (dashed, right axis)

The same divergence of emissions in token amounts vs. dollar-value shown in figure 11 for decaying emission schedules is visible for networks applying constant token emissions, see figure 12. All but The Graph are in the quadrant for „KPI-driven, constant emission schedule“ (4.1.4): their emissions do not only depend on time, which is why their dashed lines aren't constant over time.

Nucypher emissions are based on their phase 1 (see 4.1.4) before merging into Threshold network, with the worklock token emissions [100] not included.
As mentioned earlier, the cover traffic for Hopr hasn't launched yet, which is why the shown actual reward emissions are different to the planned 1% of total supply until month 27, see [60].
Covalent nodes couldn't fully claim rewards between month 3 and 7 related to the Nomad hack on Moonbeam [91]. Similar to NYM in figure 11, more recently launched networks (or reward emissions in the case of Covalent) spent less on their token emissions and - given lower prices - also in dollar terms.

This last observation led to the question if reward emissions of more recently launched networks are lower in general. Figure 13 shows that this doesn't hold in general since networks like Arweave and Livepeer with reward emissions of several years now (indicated by darker circles) emitted lower levels compared to some of the recently launched networks like Helium (5g, MOBILE), Pollen or Akash.
However, if we contrast the relative token emissions to the market capitalization (measured by the fully diluted valuation at launch of the rewards) we can observe an inverse correlation, though quite dispersed. We leave a more detailed analysis of this relationship for future research.

[14] Using the estimated maximum token supply and first available public price after launch of the reward emissions.[102]

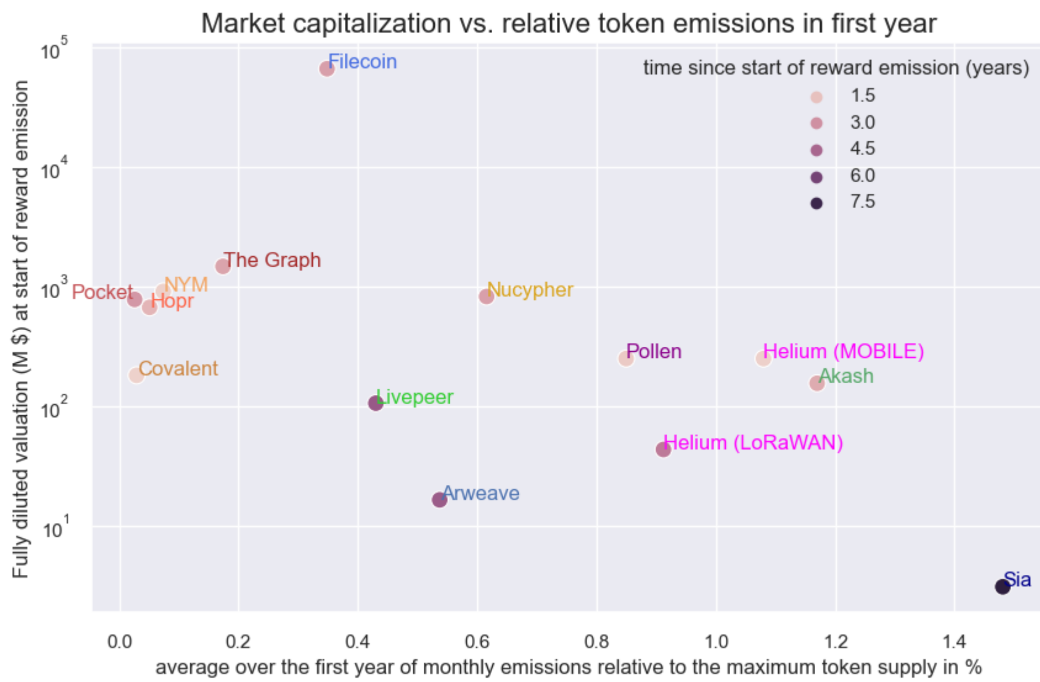

Figure 13: The average monthly token rewards relative to the estimated maxiumum token supply vs. the fully diluted valuation at start of the reward emissions[14]

5.3 Comparison to Bitcoin and Ethereum

Figure 14 shows the cumulative token emissions of our selected networks relative to their maximum token supply as introduced in section 5.1 together with the corresponding timeseries for miner rewards of Bitcoin [103] and Ethereum [104] as reference points to help putting these values into perspective.

First of all, the general pattern of decaying reward emissions is also reflected in the concave shape of those cumulative reward emissions shown in figure 14: After one year the relative emissions cumulate to less than 12% of total token supply for most of our selected networks, after two years they sum to less than 25% and after the first four years to less than 45%.
Secondly though, it is interesting to see that the relative emissions for miners on Ethereum (dotted line) track the average over our selected networks (blue solid line) quite well.

Using the numbers shown in figure 14, we can also put the dollar-values of the emitted token rewards presented in section 5.2 into perspective: Bitcoin issued roughly 30% of its total supply in the first two years after 09/2010 (when we have data on miner subsidies available[15]), which equaled approximately 30 million dollar.
However, when we consider the full first four years that we show in our charts, the emitted rewards sum to over 40% of the total BTC supply, the equivalent of roughly 1.3 billion dollars. That large dollar amount is caused by the positive pricce momentum in 2013 falling into that timerange [103].

The price for ETH saw postivie momentum already in its first two years, hence roughly 18% of issued supply[16] for rewards converted to around 710 million dollar. The range of the first four years includes the 2018 peak of the ETH price back then, such that the sum of token reward emissions equaled around 6 billion dollars for that timerange (corresponding to 30% of the estimated total supply emitted as rewards).

[15]Available data for Bitcoin miner revenues start in month 21 - we couldn't find data on miner revenues prior that.
[16]Total supply based on an assumed maximum supply of 120 million ETH

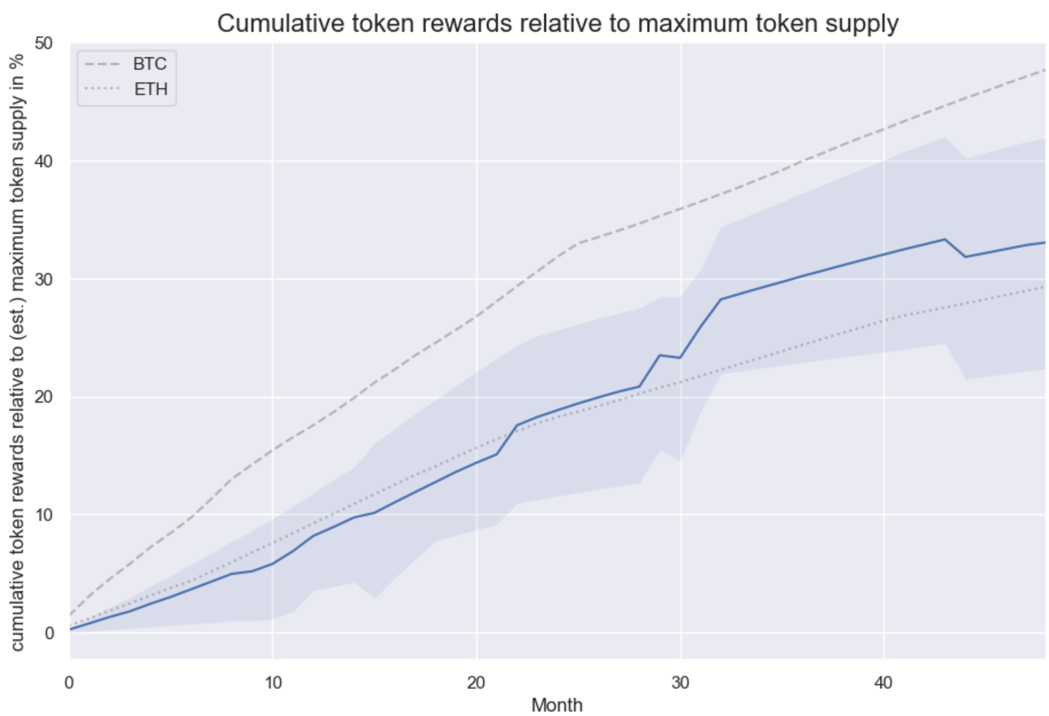

Figure 14: Both the blue line (average over all networks) and the shaded area (interquartile-range of data points) are concave over time reflecting the predominantly decaying emissions. After 12 months less than 12% of total supply is emitted for service node rewards. After two years that range is between 15% and 25%. The emissions for Ethereum (dotted line) are in line with the average of the cumulative emissions of our selected networks.

6 Conclusion and outlook

Analysing the emission schedules of 16 selected Web3 infrastructure networks we established four classes that token reward schedules follow, each a combination of a fixed (only time depended) or KPI-driven emission function and a decaying or constant shape of those emissions.

When analysing the timeseries of emissions (relative to the networks' maximum token supply) focused around, but not limited to service nodes, we observed that they follow similar ranges despite different trajectories and timings of peaks related to the characteristics of their class:

- Monthly relative emissions range from 0.2% to 1.2% in the first two years and then decrease to 0.7% and below afterwards.
- Consequently, cumulative token rewards are concave over time: after one year they are mostly below 12%, after the first two years below 25% and after four years below 45% of the maximum token supply.
- We also observed an inverse (yet dispersed) relationship of those emission levels and the market capitalization at start of the reward emissions in general.

Lastly, converted to dollar-values, those emissions follow a very different trajectory (also true across classes), impacted by price fluctuations mostly related to the positive market conditions in 2021. This is relevant if we consider that (part of) the rewards for service nodes/ the supply-side need to cover their operating costs (sooner or later): excess emissions (in dollar-terms) as seen in 2021 are not a problem per se, but they can lead to sell pressure (profit taking) of node operators. This in turn might lead to downward pressure on the token price triggering a downward spiral as operations become less profitable and force even more selling of tokens. In the worst case, node operators might even decide to shut down operations to the extend that it impacts the network supply capacity negatively.

Analysing these dynamics of token rewards, their dollar-value and the networks' supply capacity is subject of future research we plan to conduct. Concretely, we want to survey the costs that occur for the operations on the supply side (including those related to staking requirements) and factors that impact those both on the network and the node level next. Once we established this understanding on the cost side, we will analyse how the income for nodes evolve over time. Furthermore we will take the different network designs into consideration to investigate how frameworks for sustainable token economies for Web3 infrastructure networks could look like.

7 Acknowledgements

We'd like to thank the teams of Viewblock.io, Spacescope, Poktscan, Covalent and Cloudmos.io for their support in collecting empirical data and understanding corresponding details. Special thanks goes to all the communities and contributors of the various discord-channels of the selected networks for their support by answering questions around the presented mechanics and data. We'd like to thank Rohan Mehta, Krzysztof Paruch, Vasily Sumanov and Yaron Velner as well, for their review and feedback to this paper.

References

[1] https://web3index.org/

[2] S. Kassab, The DePIN Sector Map. https://messari.io/report/the-depin-sector-map. 2023

[3] https://poktscan.com/

[4] https://viewblock.io/arweave/stat/tx?time=month

[5] https://dashboard.starboard.ventures/capacity-services#network-storage-capacity

[6] https://dashboard.starboard.ventures/fvm

[7] https://explorer.helium.com/iot

[8] https://www.sdxcentral.com/articles/interview/nova-labs-builds-out-helium-based-decentralized-5g-network-via-t-mobile/2022/09/

[9] M. Grigore, State of The Graph Q1 2023. https://messari.io/report/state-of-the-graph-q1-2023. 2023

[10] S. Voshmgir, M. Zargham, Foundations of Cryptoeconomic Systems. 2020

[11] G. Wuollet, Tokenology: Moving beyond 'tokenomics', https://a16zcrypto.com/content/article/beyond-tokenomics-tokenology/. 2023

[12] https://coinscouts.io/token/depin/

[13] https://www.coingecko.com/en/global-charts

[14] R. Hang, Z. Yan, X. Liang, L.T. Yang, How Can Incentive Mechanisms and Blockchain Benefit with Each Other? A Survey. 2022

[15] R. Lamberty, A. Poddy, D. Galindo, D. de Waard, T. K"olbel, D. Kirste, Efficiency in Digital Economies - A primer on Tokenomics. 2023

[16] B.J. Drasch, G. Fridgen, T. Manner-Romberg, T. et al. The token's secret: the two-faced financial incentive of the token economy. Electron Markets 30, 557–567. 2020.

[17] C. Mendes, Tokenomics & Incentivization Strategies. https://taikai.network/blog/academy-series-11-tokenomics-incentivization-strategies. 2022.

[18] K. Samani, New models for utility tokens. https://multicoin.capital/2018/02/13/new-models-utility-tokens/. 2018

[19] U. Kabalic, Valuing burn-and-mint A net present value approach, https://blog.uros.kalabic.rs/valuing-burn-and-mint. 2023.

[20] U. Kabalic, Adequate burn-and-mint rewards Sustainably rewarding miners in a burn-and-mint economy, https://blog.uros.kalabic.rs/adequate-burn-and-mint-rewards. 2023.

[21] Giulia Fanti, Leonid Kogan, Sewoong Oh, Kathleen Ruan, Pramod Viswanath, and Gerui Wang.Compounding of wealth in proof-of-stake cryptocurrencies, 2018.

[22] Tascha Labs, The curious effect of token supply on price, https://taschalabs.com/the-curious-effect-of-token-supply-on-price/. 2022

[23] Tascha Labs, The #1 Tokenomic Mistake of Web3 Platforms (W/ 3 Hidden Costs Not Obvious on Day 1), https://taschalabs.com/the-1-tokenomic-mistake-of-web3-platforms-w-3-hidden-costs-not-obvious-on-day-1/. 2023

[24] https://6thman.ventures/writing/we-analyzed-5000-token-unlocks-this-is-what-we-found/. 2023

[25] https://6thman.ventures/writing/simulating-token-economies-motivations-and-insights/

[26] S. Williams, V. Diordiiev, L. Berman, and I. Uemlianin, Arweave: A Protocol for Economically Sustainable Information Permancece. 2019

[27] The Arweave Project, The Arweave Network is Now Running Succinct Random Proofs of Access (SPoRA), https://arweave.medium.com/. 2021

[28] https://list.weavescan.com/

[29] https://ar.io/what-is-ario/

[30] https://github.com/ArweaveTeam/arweave/blob/master/apps/arweave/src/ar_inflation.erl

[31] https://docs.filecoin.io/basics/what-is-filecoin/overview/

[32] https://spec.filecoin.io/systems/filecoin_mining/miner_collaterals/

[33] https://spec.filecoin.io/#section-algorithms.pos

[34] https://filmine.io/

[35] https://spec.filecoin.io/#section-systems.filecoin_token.block_reward_minting.simple-minting

[36] https://spec.filecoin.io/#section-systems.filecoin_token.block_reward_minting.baseline-minting

[37] https://observablehq.com/@242d00a75ac1ec36/fip_432

[38] D.L. Bernardineli, G. Lefundes, Sustainability Goal achieved: Filecoin network crosses baseline target, https://medium.com/block-science/sustainability-goal-achieved-filecoin-network-crosses-baseline-target-cec13a3ed8f.2021

[39] D. Vorick and L. Champine Sia: Simple Decentralized Storage. 2014

[40] https://docs.sia.tech/get-started-with-sia/siacoin-total-supply

[41] Storj Labs Inc.: Storj: A Decentralized Cloud Storage Network Framework. 2018

[42] G. Ouri, A. Bozanich: AKT: Akash Network Token & Mining Economics. 2020

[43] https://www.mintscan.io/akash/proposals

[44] https://github.com/gosuri/akt20/blob/main/README.md

[45] D. Petkanics, E. Tang: Livepeer Whitepaper. 2018

[46] https://livepeer.org/primer

[47] https://dune.com/queries?category=decoded_project&namespace=livepeer&blockchains=arbitrum&contract=Bonding

[48] https://forum.livepeer.org/t/transcoding-verification-improvements-fast-full-verification/1499

[49] https://docs.livepeer.org/guides/orchestrating/get-started

[50] https://www.livepool.io/#get_started

[51] Livepeer Team, A primer on Livepeer's probabilistic micropayments, https://medium.com/livepeer-blog/a-primer-on-livepeers-probabilistic-micropayments-e16788b29331. 2021

[52] Render Token (RNDR) Whitepaper. 2017

[53] https://know.rendertoken.com/getting-started/using-layer-2-l2

[54] https://github.com/rndr-network/RNPs/blob/main/Approved%20and%20on%20the%20Roadmap/RNP-002.md

[55] https://know.rendertoken.com/documentation/rndr-user-manuel/m-proof-of-rndr

[56] https://snapshot.org/#/rndrnetwork.eth/proposal/0xf8f314b4f960631ef9e3d86e3dd99fc97ffea74513f7f0cf87e729f7d22e28

[57] https://github.com/rndr-network/RNPs/blob/main/Full%20Approval/rnp-001-bme.md

[58] https://docs.google.com/spreadsheets/d/1vgNamfJsJeCOUnFGtrdBw7GJCtN25bXEIFOluJQAO64/edit#gid=3655243

[59] hopr: The Book of HOPR. hoprnet.org, 2021

[60] S. Brügel, Introducing: The HOPR token, https://medium.com/hoprnet/introducing-the-hopr-token-bd4a2a31fc7f. 2021

[61] https://docs.hoprnet.org/core/proof-of-relay

[62] C. Diaz, H. Halpin and A. Kiayias, The Nym Network: The Next Generation of Privacy Infrastructure. 2021

[63] https://nymtech.net/docs/architecture/network-overview.html

[64] NYM, Staking in Nym - introducing mainnet mixmining, https://blog.nymtech.net/staking-in-nym-introducing-mainnet-mixmining-f9bb1cbc7c36. 2022

[65] C. Diaz, H. Halpn and A. Kiayias, Reward Sharing for Mixnets. Cryptoeconomic Systems 2(1). 2022

[66] https://github.com/nymtech/rewardsharing-simulator

[67] https://docs.pokt.network/learn/glossary/

[68] https://docs.pokt.network/learn/protocol/servicing/#proof-of-relay-evidence

[69] https://forum.pokt.network/t/pip-7-consensus-rule-change-validator-servicer-split-validator-consolidation/1272

[70] https://github.com/orgs/pokt-network/projects/142/views/12?pane=issue&itemId=11846695

[71] https://forum.pokt.network/t/pup-22-further-reduction-of-emission-numbers-fren/3235

[72] https://forum.pokt.network/t/pup-19-increase-validator-reward-from-1-to-5-immediately/3169

[73] https://docs.helium.com/faq/helium-network/

[74] https://docs.helium.com/blockchain/proof-of-coverage

[75] https://github.com/helium/HIP/blob/main/0010-usage-based-data-transfer-rewards.md

[76] Helium Foundation, Helium Community approves HOP 20, https://medium.com/helium-foundation/helium-community-approves-hip-20-127cf75303bf.2020

[77] https://github.com/helium/HIP/blob/main/0020-hnt-max-supply.md#detailed-explanation

[78] https://docs.helium.com/vote-escrow/voting-power/

[79] https://docs.helium.com/5g-on-helium/

[80] H. Leroy, A. Golding, T. Shaughnessy, Pollen and Helium: The race to bootstrap a 5g network, https://members.delphidigital.io/reports/pollen-and-helium-the-race-to-bootstrap-a-5g-network#dewi-battle-royale–helium-vs-pollen. 2022

[81] https://deploy-preview-985–helium-docs.netlify.app/5g-on-helium/mining-5g/

[82] https://docs.helium.com/mobile/proof-of-coverage

[83] https://github.com/helium/HIP/blob/main/HIP-solana-parameters/token-emissions-as-of-solana-migration.pdf

[84] https://docs.helium.com/helium-tokens/mobile/#fn-4

[85] https://docs.pollenmobile.io/pollen-mobile-docs/white-paper/key-pollen-network-actors

[86] https://docs.pollenmobile.io/pollen-mobile-docs/white-paper/network-infrastructure

[87] https://docs.pollenmobile.io/pollen-mobile-docs/white-paper/payments

[88] Covalent, Covalent Network Whitepaper, https://www.covalenthq.com/static/documents/Covalent%20Whitepaper%20M 2022

[89] https://www.covalenthq.com/docs/cqt-network/network-rewards/#network-operator-reward-models

[90] https://www.covalenthq.com/staking/#/

[91] https://www.covalenthq.com/blog/nomad-bridge-hack-covalent-response/

[92] B. Ramirez, The Graph Network In Depth - Part 1, https://thegraph.com/blog/the-graph-network-in-depth-part-1/.2019

[93] B. Ramirez, The Graph Network In Depth - Part 2, https://thegraph.com/blog/the-graph-network-in-depth-part-2/.2019

[94] Ryabina, Graph Network. Fee Cut and Rewards Cut: How It Works, https://ryabina.medium.com/graph-network-fee-cut-and-rewards-cut-hot-it-works-625fded9c827. 2020

[95] https://thegraph.com/explorer

[96] https://thegraph.com/docs/en/network/indexing/

[97] https://thegraph.academy/glossary/

[98] M. Egorov, D. Nunez, M. Wilkison, NuCypher: A proxy re-encryption network to empower privacy in decentralized systems, https://github.com/nucypher/whitepaper/blob/master/whitepaper.pdf.2018

[99] M. Egorov, M. Wilkison, A. Hassard, NuCypher Network: Staking Protocol & Economics, https://github.com/nucypher/whitepaper/blob/master/economics/staking_protocol/NuCypher_Staking_Protocol_Econor 2020

[100] Gauntlet, WorkLock Assessment An analysis of the NuCypher WorkLock mechanism and Staking economics. 2020

[101] M. Luongo, M Wilkison, The story of Threshold so far: The KEANU vote, tBTC v2, and the 2021 roadmap, https://blog.threshold.network/the-story-of-threshold/. 2021

[102] https://www.coingecko.com/ for price data

[103] https://www.blockchain.com/explorer/charts/ (miners-revenue and transaction-fees)

[104] https://www.galaxy.com/research/insights/breakdown-of-ethereum-supply-distribution-since-genesis/

A Roles of the supply-side of Web3 infrastructure networks

Network (Token)	**Service provided**	**Service node**	**Validator**	**Delegator**	**Gateway**
Arweave [26] (AR)	Storage	Miner (also validator): store/retrieve data	Proof of access (SpoRA, [27]) on Arweave blockchain	-	(Easier) access to read/write data on the permaweb, several [28], e.g. ar.io [29]
Filecoin [31] (FIL)	Storage	Storage miner (also validator): store/retrieve data, stake FIL [32]	Verify storage via proof of replication and proof of spacetime on Filecoin blockchain [33] (initiate slashing if consensus that this isn't the case)	-[17]	-
Sia [39] (SIA)	Storage	Hosts store (encrypted) data pieces	Miners operate the SIA blockchain (proof of storage) on Sia blockchain	-	-
Storj [41] (STORJ)	Storage	Storage node / NAS (network attached storage device) store/ retrieve data	Validations (audits) triggered by users before sending micropayments (Satelites or users store metadata on node reputation, billing etc. based on those), Ethereum blockchain, zksync for settlement	-	DCS connectors enable app developers to store, retrieve, manage data on cloud
Akash [42] (AKT)	Compute	Provider: offer computing cycles to earn fees, need to stake AKT in proportion to hourly income earned	Validator operates Akash blockchain, validates/ relays transactions	Stake with validator for share of AKT block rewards	-
Livepeer [45] (LPT)	Video transcoding, streaming	Transcoders transcode videos to earn fees (in ETH)	Orchestrator participate in work verification protocol (fast and fulll verification [48]) on Arbitrum[18]	Stake LPT with orchestrators, earn share of fees and staking rewards	Orchestrators bid for transcoding requests and communicate with transcoder
Render [52] (RNDR)	Rendering	Node operator provide GPU compute to creators	Proof of rndr (quality assessment) validated by number of inputs, e.g. creator approval, automated checks [55], tx settlement moved to Polygon [53], but about to change to Solana[19]	-	-

Table 1: Roles of the supply-side of protocols providing storage and compute

[17]Protocols like Filmine [34] started to allow FIL holders to lend out their FIL to storage miners in exchange for a liquid staking derivative, which mimics a delegation process

[18]Switched from Ethereum blockchain in February 2022.

[19]As voted recently in RNP 002 [54]

[20]But planned - hence delegation rewards are (obviously) not included in our empirical data.

[21]To some extends mix nodes are part of the validator role as well as they generate the measurement messages used to assess the quality of service, see details on the proof of mixing in section 6.4 of the Whitepaper [62]

[22]With the switch to Solana a ve-model was introduced allowing staking and delegation of HNT for governance [78]

[23]Such as authentification, data metering. Only used in early stage - as mentioned in [86] Pollen moved away from access gateways.

[24]Whilst Indexers get rewarded via token rewards, curators earn a share of the query fees for the curated subgraph (using a bonding curve mechanism, see [93].

Network (Token)	**Service provided**	**Service node**	**Validator**	**Delegator**	**Gateway**
Hopr [59] (HOPR)	Message routing/ mixing	1) Mix nodes routing packages through the mixnet, 2) Cover traffic nodes generate traffic to increase privacy for all messages	Mix nodes also perform proof of relay [61], settlement on Ethereum	Delegation not enabled yet[20]	-
NYM [62], [63] (NYM)	Message routing/ mixing	Mix node route packages through the mixnet, stake NYM	Validators operate Nyx blockchain (PoS), determine which nodes are included within the network, Mix nodes as part of proof of mixing[21]	Stake NYM with mix nodes (potentially validators and gateways as well)	Send incoming request into mixnet, act as message storage for clients, stake as well
Pocket [67] (POKT)	RPC/ data routing	Serve the RPC requests	Top 1000 nodes (by stake) don't operate as service node but produce blocks (see [69])	-	Stake pokt on behalf of apps, see [70]
Helium (LoRaWAN) [73] (HNT)	IoT network coverage	Hotspots provide network coverage	Hotspots also provide proof of coverage, Solana used for settlement (switch from Helium blockchain in 04/2023)	Not related to supply[22]	Gateway applications build on top
Helium (5g) [79], [80] (MOBILE)	5g mobile data network coverage	Hotspots provide network coverage, proof of coverage	Validators operate Helium blockchain (switch to Solana 04/2023)	-	Freedomfi and bobber as access gateways [81]
Pollen (5g) [85], [80] (PCN)	5g mobile data network coverage	Flowers: 5g antennas to provide local 5g	Honeybees/bumblebees: proof of coverage, Solana used as blockchain for settlement	-	Access gateways orchestrating access to flowers[23]
Covalent [88] (CQT)	Blockchain data indexing/ querying	Network operators serve query/API requests	Auditors to ensure correctness of network operators' work, settlement of transactions on Moonbeam	Stake with network operators	-
The Graph [92], [93] (GRT)	Blockchain data indexing/ querying	Indexer offer indexing/queries of data, curator signals subgraphs that are worthy to be indexed (often subgraph developer), stake GRT[24]	Arbitraion charter setting standards for proof of indexing, fisherman able to challenge those [96], Subgraph Availability Oracle checks availability of subgraph manifest [**?**], settlement on Ethereum and Arbitrum	Stake with indexers	The Graph Explorer [95]
Nucyper [98] (NU)	Access control	PRE Nodes Encryptor (re-) encrypt data, enforce access policy	Settled on Ethereum first, then switch to Polygon	Stake with nodes	-

Table 2: Roles of the supply-side of protocols providing data/message routing/mixing (incl. RPC), wireless network, data access/indexing and access control services

B Data sources for the empirical analysis

Network	Sources	Comment
Arweave	https://viewblock.io/arweave/stats	
Filecoin	https://docs.spacescope.io/ https://dashboard.starboard.ventures/ https://stats.filecoin.io/	
Sia	https://siastats.info/api https://siastats.info/index	
Storj	https://storjstats.info/d/storj/storj-network-statistics https://stats.storjshare.io/	
Akash	https://cloudmos.io/akash/dashboard https://www.mintscan.io/akash https://akash.aneka.io/charts https://docs.google.com/spreadsheets/d/ 1MUULetp59lgNq0z4ckVI51QdtMGvqt KOW8wRfX5R8yY/edit#gid=2130333819	
Livepeer	https://dune.com/stronk/livepeer-arbitrum https://dune.com/queries/1398261	Extended existing queries, e.g. to query orchestrator level data
Render	https://github.com/rndr-network/RNPs/ blob/main/Full%20Approval/ rnp-001-bme.md	Only used the planned emissions for the emission schedule classification
Hopr	https://dune.com/hoprnet https://dune.com/queries/2037368 https://network.hoprnet.org/	Used the dune queries to aggregate the rewards paid to stakers so far (as mentioned, the cover traffic isn't live yet).
NYM	https://mixnet.api.explorers.guru/api/ https://status.notrustverify.ch/grafana/d/ l71MWkX7k/ntv-mixnode?orgId=1 https://nym.explorers.guru/ https://explorer.nymtech.net/ https://validator.nymtech.net/api/v1/ mixnodes/	Rewards prio 12/2022 approximated using grafana as querying onchain data not finished at time of writing
Pocket	https://poktscan.com/api/graphql (https://fallback-api.poktscan.com/) https://poktscan.com/explore	Poktscan migrating v1 api to v2 api (hence used fallback endpoint recently)
Helium (LoRaWAN, 5g)	https://api.helium.io/v1/ https://docs.helium.com/oracles/oracle-data https://www.heliumboard.com/index https://heliumanalytics.io/monthly-reward-distribution/	The Helium API was deprecated with the move to Solana end of April 2023, see oracle-data link and [83] for details
Pollen	https://api.pollenmobile.io/explorer https://explorer.pollenmobile.io/	Note that Pollens API endpoint is stale since 12/18/2022
Covalent	https://www.covalenthq.com/staking/#/	
The Graph	https://dune.com/abarmat/The-Graph-Overview https://dune.com/queries/1844721 https://graphscan.io/ https://thegraph.stake-machine.com/	Extended the queries of available dashboards by details, e.g. GRT claimed by indexers
Nucypher	https://dune.com/queries/2036542 https://dune.com/queries/2036596	

Table 3: Sources used to collect data for the empirical analysis

Above table was created for the original version of this paper on May 11th 2023. Meanwhile detailed information to the sources, data (incl. notebooks) for each network is provided here: https://github.com/1kx-network/web3infrastructure_tokenomics/tree/main