



The road to decentralization: Optimal coverage on Decentralized Physical Infrastructure Networks (DePIN)

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ABSTRACT

Decentralized Physical Infrastructure Networks (DePIN) represent an emerging organizational form for operating physical infrastructure through blockchain-based coordination. DePIN through decentralized protocols and token-based payment mechanisms incentivize independent agents to deploy, maintain, and monetize real-world infrastructure, such as wireless networks, storage units, or sensors. This article presents a first formal economic analysis of DePIN architectures, modelling investment decisions under network effects in a blockchain-native Decentralized Autonomous Organization (DAO), with protocol-defined reward schemes. It establishes the equilibrium conditions that support decentralized provision, where token prices internalize participation, service reliability, and network coverage. Furthermore, it identifies a minimum viable coverage threshold determined by costs and network effects. Through a multi-agent machine learning simulation, we confirm that decentralized provision improves efficiency compared to centralized models. The results support the economic viability of DePIN and provide design guidelines for future decentralized infrastructure protocols. Finally, we propose a DAO incentive mechanism to implement First Best provision in Decentralized Physical Infrastructure Networks.

1. Introduction and literature review

Decentralized Physical Infrastructure Networks (DePIN) allow individual agents to contribute physical resources to a network organized and managed through blockchain protocols that use native tokens as payment. DePIN hold relevance for finance research as they illustrate how economic benefits can arise from the decentralized coordination and allocation of infrastructure resources (Surve and Khandelwal, 2023; Pereira et al., 2019). In contrast to the traditional centralized provisioning by large corporations, governments, or monopolies, DePIN redefine markets that traditionally pose high barriers to entry such as considerable initial costs or regulation. In this article, we study DePIN as a decentralized network-effects industrial organization model and analyse the financial implications of its implementation under various markets.

Beyond reviews on advantages of blockchain technology for decentralized allocation (Ali et al., 2021; Lage et al., 2022; Islam and Apu, 2024; Ahmed, 2025), the literature on Distributed Energy Resources (DER) in peer-to-peer microgrids (Boumaiza, 2024a,b;

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Dong et al., 2022) provides a descriptive background (Pop et al., 2018; Mezquita et al., 2022; Seven et al., 2020; Bhavana et al., 2024; Thukral, 2021; Yap et al., 2023; Karumba et al., 2023), although it does not specifically address DePIN. Building on these antecedents, the literature on DePIN is limited and mostly descriptive (Zheng et al., 2025). Lin et al. (2025) and Liu and Omote (2025) provide an exploratory approach to the design, operation, market capitalization and challenges. The first adopts a technical approach, focusing on algorithms to strengthen security, reduce costs and improve scalability and privacy. The latter presents a consensus protocol using eIDs within blockchain to increase verifiability and traceability. Other works available in repositories reproduce a general framework (Ballandies et al., 2023; Sarkar, 2023) and examine the transitions toward decentralized autonomous machines (Castillo et al., 2025). Andrew and Ballandies (2025) outlines the boundaries between DePIN and traditional collaborative infrastructures methods, and Mao et al. (2025) studies computing-power DePIN.

Existing contributions in conferences examine vulnerabilities in resource sharing (Caprolu et al., 2025), solutions to improve scalability (Fan and Xu, 2024; Fan, 2024), and comparisons of decentralized models (von der Assen et al., 2024). The pre-print by Millionis et al. (2025) approaches a model to strengthen security, incorporating game theory to verify the level of service provided in DePIN.

This article contributes to the incipient finance research on DePIN by proposing a formal network-effects model, in the style of Economides and Himmelberg (2013), to formalize the economic mechanism underlying DePIN (Section 2). Using a multi-agent machine learning approach similar to that of Soria et al. (2023), we further simulate strategic interactions between producers and users across different markets (Section 3). The results support the model and provide insights into prices, network effects, coverage levels, and the incentives and costs of participation. In Section 4, we propose an incentive mechanism to implement socially optimal coverage through a DePIN Decentralized Autonomous Organization (DAO). Sections Appendix A to Appendix D include more detailed explanations of the situation of DePIN, mathematical proofs, the simulation results and a proposal of DAO mechanism to implement first-best outcomes under DePIN provision.

2. Foundations of DePIN and analytical model

A DePIN is composed of physical infrastructure nodes, such as sensors, wireless access points, storage or processing units. These are organized through blockchain-based protocols (e.g. *Proof-of-Physical-Work*), that verify and record contributions in a shared ledger (Liu and Omote, 2025; Almadani et al., 2023; Narayanan et al., 2016). DePIN should not be confused with Distributed Energy Resources (DER), which integrate smart devices to optimize distribution and consumption (Karumba et al., 2023; Maksymyuk et al., 2020). Although these systems use blockchain for transaction traceability and monitoring (Yap et al., 2023; Seven et al., 2020; Wang et al., 2020), they operate within centralized or institutional architectures, without providing the full decentralization that DePIN enables.

A token is a digital asset that can be sold or used to acquire services (Treiblmaier, 2023; Tanveer et al., 2025). In DePIN, tokens are distributed proportionally to contributions to the network, according to variables such as quantity or quality provided by the node in a *contribute-to-earn* manner. Tokens incentivize participation, organize cooperation and optimize the operational efficiency of it (Treiblmaier, 2023).

In most protocols, tokens grant voting rights to participants in the governance of the DePIN network through Decentralized Autonomous Organizations (DAOs), which automate and validate the decision-making process using smart-contracts (John et al., 2023; Cong and He, 2019). Fig. 1 summarizes this intersection between infrastructure, blockchain, Tokenomics and DePIN applications. More information on DePIN functioning in Appendix A. Appendix B presents a summary of the main projects shaping this ecosystem, along with an approximation of their capitalization.

Building on these basic operational specifications, we create a dynamic model that captures the functional aspects of a DePIN network.

Consider a world with discrete time periods $t = 0, 1, 2, \dots$ and an infinite horizon with common discount factor $\delta \in [0, 1)$. A continuum of users $i \in [0, 1]$ have valuations $v_{i,t}$ independently drawn from distribution F with density f , continuous on $[0, 1]$ and satisfying standard regularity conditions. This captures heterogeneity in preferences and reflects a realistic market with diverse demand. Formally, the continuum representation simplifies aggregation while modelling a market of many small, independent participants whose individual decisions collectively determine network coverage.

User utility exhibits network effects, meaning that it depends not only on individual consumption but also on the overall network coverage, so that a higher provision level increases the value of the service for all users (Katz and Shapiro, 1994). The more providers participate and the broader the coverage, the greater the perceived utility, as seen in communication networks, transport and other infrastructures. Utility is given by

$$u_t(v_{i,t}, N_t) = v_{i,t}(\phi + \eta N_t^\alpha) - p_t, \quad (1)$$

where $\phi \geq 0$ represents the intrinsic value of the service in the absence of network effects (a higher ϕ implies weaker dependence on the network, while $\phi = 0$ means the good derives value solely from network participation). The parameters $\eta > 0$ and $\alpha > 0$ capture the strength and elasticity of the network effect, respectively, and $N_t \in [0, 1]$ denotes DePIN coverage at time t . Intuitively, N_t can be understood as the share of total area or users effectively covered by the network—e.g., in a Wi-Fi DePIN, it would correspond to the percentage of locations with active service.

We assume $\eta > 0$, meaning broader coverage increases perceived value. If growth causes congestion or overcrowding, the opposite effect ($\eta < 0$) may occur (Karhu et al., 2024; Liu et al., 2022). While our framework could accommodate such cases,

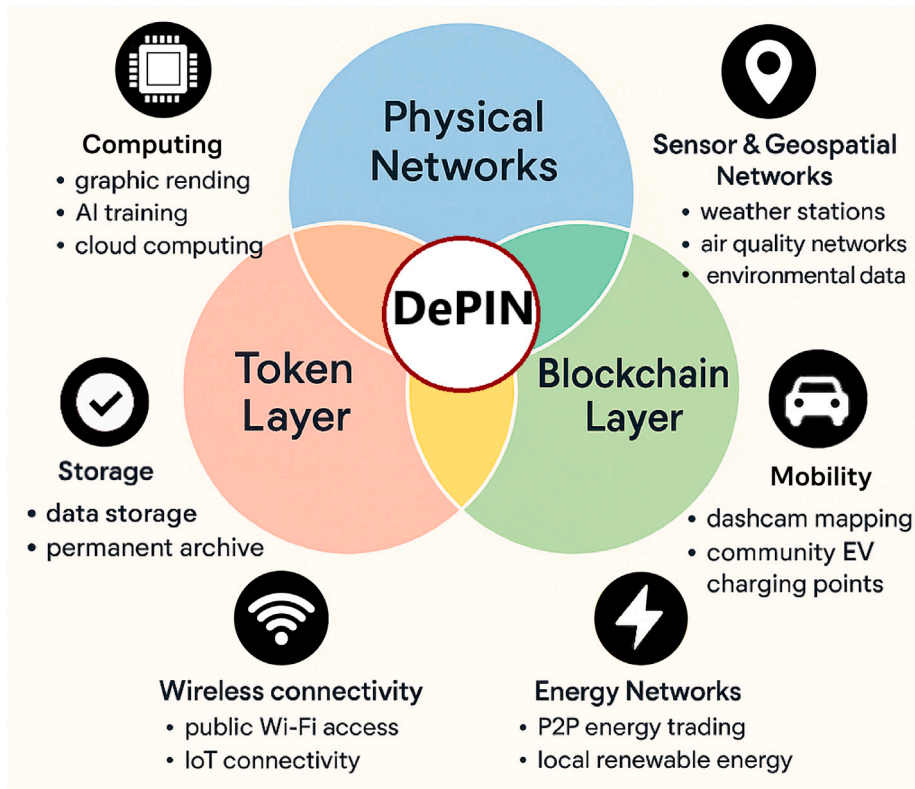


Fig. 1. DePIN architecture and examples of applications.

the positive-network-effect assumption is more suitable for DePIN architectures, where additional nodes enhance service quality and reliability.

The restriction $\alpha > 0$ together with $N_t \in [0, 1]$ is a modelling choice ensuring monotonicity of the externality. Allowing $\alpha < 0$ would invert the relationship (e.g., $\eta/N_t^{|\alpha|}$), changing its interpretation but not the model itself.

A user buys iff $v_{i,t} \geq \frac{p_t}{\phi + \eta N_t^\alpha}$. Hence, market demand satisfies

$$Q_t = 1 - F\left(\frac{p_t}{\phi + \eta N_t^\alpha}\right) \tag{2}$$

Solving for price using the inverse cumulative distribution function gives the inverse demand

$$p(Q_t, N_t) = (\phi + \eta N_t^\alpha) F^{-1}(1 - Q_t) \tag{3}$$

In fulfilled-expectations equilibrium, quantity demanded equals coverage, $Q_t = N_t$, and the equilibrium inverse demand is

$$p(N_t, N_t) = (\phi + \eta N_t^\alpha) F^{-1}(1 - N_t) \tag{4}$$

Proposition 1 (Non-monotonic Price Under Strong Network Effects). Suppose $f(1) > 0$ and $f(0) > 0$. If either $\alpha < 1$ with $\eta > 0$, or $\alpha = 1$ with $\eta > \phi/f(1)$, then $p(N, N)$ is increasing for small N and decreasing for N near 1. Hence, there exists a unique $N_{\text{peak}} \in (0, 1)$ with

$$\frac{dp(N_{\text{peak}}, N_{\text{peak}})}{dN} = 0, \quad p_{\text{max}} := p(N_{\text{peak}}, N_{\text{peak}}) = \max_{N \in [0,1]} p(N, N) \tag{5}$$

Proof in Appendix C.1.

DePIN becomes relevant in markets that (a) present network effects and (b) are traditionally organized through by monopolies/oligopolies. Let $\mathbb{I}/K \geq 0$ denote a per-period fixed/entry cost that is paid only by the provider(s) (i.e. $K_t \equiv \left| \{i \in I : N_{i,t} > 0\} \right|$). The analysis goes as follows: we first describe the optimal choice by a monopoly, followed by oligopolistic competition under Cournot competition, which is then used to calculate the perfect competition outcome as $K \rightarrow \infty$. Finally, we describe the Social Optimum. Section 3 simulates the results and Section 4 describes the mechanism to achieve the Social Optimum through a Decentralized Autonomous Organization (DAO) DePIN protocol.

Monopoly

The monopolist's discounted expected profit is

$$\Pi^M = \sum_{t=0}^{\infty} \delta^t \left[N_t p(N_t, N_t) - c N_t - \mathbb{I} \cdot \mathbf{1}\{N_t > 0\} \right] \tag{6}$$

The per-period static problem is

$$\max_{N \geq 0} \Pi(N) = N p(N, N) - c N - \mathbb{I} \cdot \mathbf{1}\{N > 0\} \tag{7}$$

For an interior choice $N^M > 0$, the first-order condition (FOC) is

$$p(N, N) + N \frac{dp(N, N)}{dN} - c = 0 \tag{8}$$

Writing $q(N) := F^{-1}(1 - N)$, we have $q'(N) = -1/f(q(N))$ and thus

$$\frac{dp(N, N)}{dN} = \eta \alpha N^{\alpha-1} q(N) - \frac{\phi + \eta N^\alpha}{f(q(N))} \tag{9}$$

Monopoly produces on the decreasing par of $p(N, N)$, where $\frac{dp(N, N)}{dN} < 0$, and must cover \mathbb{I} . If the monopoly chooses an interior $N^* > 0$, then $\frac{dp(N^*, N^*)}{dN} < 0$ and $N^* [p(N^*, N^*) - c] \geq \mathbb{I}$. The profit with $N > 0$ is $\Pi(N) = N [p(N, N) - c] - \mathbb{I}$. Interior optimality requires $\Pi(N^M) \geq 0$, so by incentive compatibility $N^M [p(N^M, N^M) - c] \geq \mathbb{I}$, implying $p(N^M, N^M) - c > 0$. From (8), $N^M \frac{dp}{dN} = c - p(N^*, N^*) < 0$, hence $\frac{dp}{dN} < 0$.

Proposition 2 (Minimum Active Coverage Under Fixed Cost). *If $p(N, N)$ is non-monotone with unique peak at N_{peak} , then the minimum coverage at which a monopoly can be active is*

$$N_{\min} = \inf \left\{ N \geq N_{\text{peak}} : N [p(N, N) - c] \geq \mathbb{I} \right\} \tag{10}$$

Proof in Appendix C.2.

Proposition 2 implies that there is a minimum critical mass for provision of coverage that depends on ϕ, η, α and the distribution of valuations ($F(v)$).

Oligopoly (Cournot)

Let K_t be the number of providers and $n_{j,t}$ the coverage of provider j , so $N_t = \sum_{j=1}^{K_t} n_{j,t}$. With per-period fixed cost $\mathbf{I}_t := \mathbb{I}/K_t$ when active, a provider's discounted value is

$$\max_{\{n_{j,t} \geq 0\}} \sum_{t=0}^{\infty} \delta^t \left[n_{j,t} p(N_t, N_t) - c n_{j,t} - \mathbf{I}_t \cdot \mathbf{1}\{n_{j,t} > 0\} \right] \tag{11}$$

In the static Cournot stage and for interior choices, the FOC is

$$\frac{\partial}{\partial n_{j,t}} \left[n_{j,t} (p(N_t, N_t) - c) \right] = p(N_t, N_t) - c + n_{j,t} \frac{dp(N_t, N_t)}{dN_t} \cdot \frac{\partial N_t}{\partial n_{j,t}} = 0, \tag{12}$$

where $\frac{\partial N_t}{\partial n_{j,t}} = 1$. In a symmetric equilibrium $n_{j,t} = N_t/K_t$, so

$$\underbrace{p(N_t, N_t)}_{\text{Competitive price}} + \underbrace{\frac{N_t}{K_t} \frac{dp(N_t, N_t)}{dN_t}}_{\text{Markup}} = c \tag{13}$$

DePIN lowers technological and organizational barriers to entry by modularizing coverage into micro-nodes and by allowing users to be producers. It reduces the effective per-node scale required to operate, spreads the per-period activity cost \mathbf{I} , and (iii) coordinates entry via token-based rewards.

Proposition 3 (Competitive Limit). *Along any sequence of symmetric Cournot equilibria with $K_t \rightarrow \infty$, the limiting coverage N^C satisfies*

$$p(N^C, N^C) = c \tag{14}$$

Proof. Taking $K_t \rightarrow \infty$ in (13) drives the markup term $\frac{N_t}{K_t} \frac{dp}{dN_t}$ to zero, yielding $p(N^\infty, N^\infty) = c$. \square

and as the number of providers K rises, the markup term vanishes and the outcome converges to the competitive condition $p(N, N) = c$.

Proposition 4 (Multiplicity of Equilibria in the Fulfilled Coverage Levels). If $p(N, N)$ is non-monotone with unique peak p_{\max} at N_{peak} , then for any $c \in (0, p_{\max})$ the equation $p(N, N) = c$ has exactly two solutions $0 < N_\ell < N_{\text{peak}} < N_h < 1$. Under monopoly, only N_h can satisfy both the FOC and the fixed-cost coverage condition; $N = 0$ is also an equilibrium if $N_h[p(N_h, N_h) - c] < I$. However, under DePIN, as K increases, both N_ℓ and N_h are equilibria, with the latter becoming the main equilibrium. Furthermore, $N^M < N_h^M \rightarrow N_h^C$.

Proof in Appendix C.3.

The decentralized move toward the competitive condition $p(N^C, N^C) = c$ favours the high-coverage branch because the monopoly/oligopoly constraint that forces production onto the decreasing branch with a sizeable I barrier is relaxed as K rises and the protocol co-funds activity. DePIN increases the number of providers K and reduces fixed costs per node, moving the market from monopoly (Eq. (8)) toward the competitive limit (Proposition 3). Decentralized provision helps select the high-coverage equilibrium N_h (Proposition 4). Next we analyse how Social Optimum provides even higher coverage (see Eq. (17) and in Section 4 we present how governance in DePIN can achieve the social planner solution.

Social Planner (Network Externality Internalization)

We define the gross benefit under fulfilled expectations by

$$B(Q, N) = \int_0^Q p(x, N) dx, \tag{15}$$

and social welfare when $Q = N$ by

$$W(N) = B(N, N) - cN - I \cdot \mathbf{1}\{N > 0\} \tag{16}$$

For any interior $N > 0$, the planner’s FOC is

$$\frac{dW}{dN} = p(N, N) + \int_0^N \frac{\partial p(x, N)}{\partial N} dx - c = 0, \tag{17}$$

where $\int_0^N \frac{\partial p(x, N)}{\partial N} dx$ captures the (positive) network externality that atomistic producers ignore. Hence, relative to the competitive condition $p(N, N) = c$, the planner sets a (weakly) higher coverage because of the positive integral term. Section 4 presents how a DAO can internalize this positive externality and achieve Social Optimum in a decentralized manner.

3. Machine learning simulation

We use a Q-learning algorithm (Zai and Brown, 2020), where we model each of the N_{users} users and N_{firms} DePIN producers as autonomous agents with separate Q-tables. At each discrete time t , the state observations are given by the DePIN nodes that observe their past supplied quantity n_i and the users that observe their past binary decision. We use ϵ -greedy action selection, where each agent k selects an action a_k following the rule:

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$$a_k = \begin{cases} \text{random action,} & \text{with probability } \epsilon_k \\ \arg \max_a Q_k(s_k, a), & \text{otherwise} \end{cases} \tag{18}$$

where ϵ_k decays gradually from an initial ϵ_0 toward a minimum ϵ_{\min} , balancing initial exploration with later exploitation.

The reward for the producers are given by:

$$r_j^{\text{firm}} = n_j \cdot \text{price} - c n_j - I \cdot \mathbf{1}\{n_j > 0\} \tag{19}$$

where “price” is determined by the aggregate supply $N_t = \sum_i n_i$ and network elasticity α . Users draw a private valuation $v_i \sim \text{Beta}(a, b)$ each period and, if they buy, get rewards given by

$$r_i = v_i + v_i^{\text{base}} N_t^\alpha - \text{price} \tag{20}$$

After observing rewards, agents update Q-tables following the rule

$$Q_k(s, a) \leftarrow (1 - \alpha) Q_k(s, a) + \alpha (r_k + \gamma \max_{a'} Q_k(s', a')) \tag{21}$$

We simulate three market structures: Monopoly ($N_{\text{firms}} = 1$), Oligopoly ($N_{\text{firms}} = 20$) and Open DePIN Network ($N_{\text{firms}} = 100$). Each with $T = 500,000$ iterations and 100 users. We compare outcomes under network-effect elasticities $\alpha \in \{0, 0.25, 0.5\}$. To assess robustness we do two experiments: valuations from a Beta (5,5) distribution (moderate dispersion around the mean), and from a Beta(1,1) distribution (i.e., Uniform(0,1)). Table 1 presents the parameters. Statistics by scenario can be found in Appendix D Table D.4. The code is available online github.com/jsoriario/DePIN/.

Fig. 2 shows results for the monopoly. Supply stabilizes around 50–60% of capacity under Beta valuations, and slightly lower under Uniform (≈ 0.45), rising modestly with α . Demand converges to ≈ 0.5 – 0.65 , significantly lower than under DePIN. These results reflect the monopolist’s ability to restrict output and maintain mark-ups. As shown in Fig. 3, when we move toward oligopoly, supply

Table 1
Simulation parameters.

General parameters	
Number of iterations, T	500 000
Number of users, N_{users}	100
Actions per firm, $ \mathcal{A}_{firm} $	10
Discount factor, δ	0.95
Learning rate (users), α_{lr}^{user}	0.10
Learning rate (firms), α_{lr}^{firm}	0.10
Initial epsilon ($\epsilon_{user}, \epsilon_{firm}$)	(1.0, 1.0)
Epsilon decay factor	0.9999
Minimum epsilon, ϵ_{min}	0.01
Firm marginal cost, c	0.05
Valuation distributions	
Beta (5,5)	$(a, b) = (5, 5)$
Uniform (1,1)	$(a, b) = (1, 1)$
Network effect elasticity, $\alpha_{network}$	{0, 0.25, 0.5}
Monopoly	$\left\{ \begin{array}{l} K = 1, \\ I = 0.4/1, \\ \text{max_supply} = 1/1 \end{array} \right.$
Oligopoly	$\left\{ \begin{array}{l} K = 20, \\ I = 0.4/20, \\ \text{max_supply} = 1/20 \end{array} \right.$
Competitive	$\left\{ \begin{array}{l} K = 100, \\ I = 0.4/100, \\ \text{max_supply} = 1/100 \end{array} \right.$

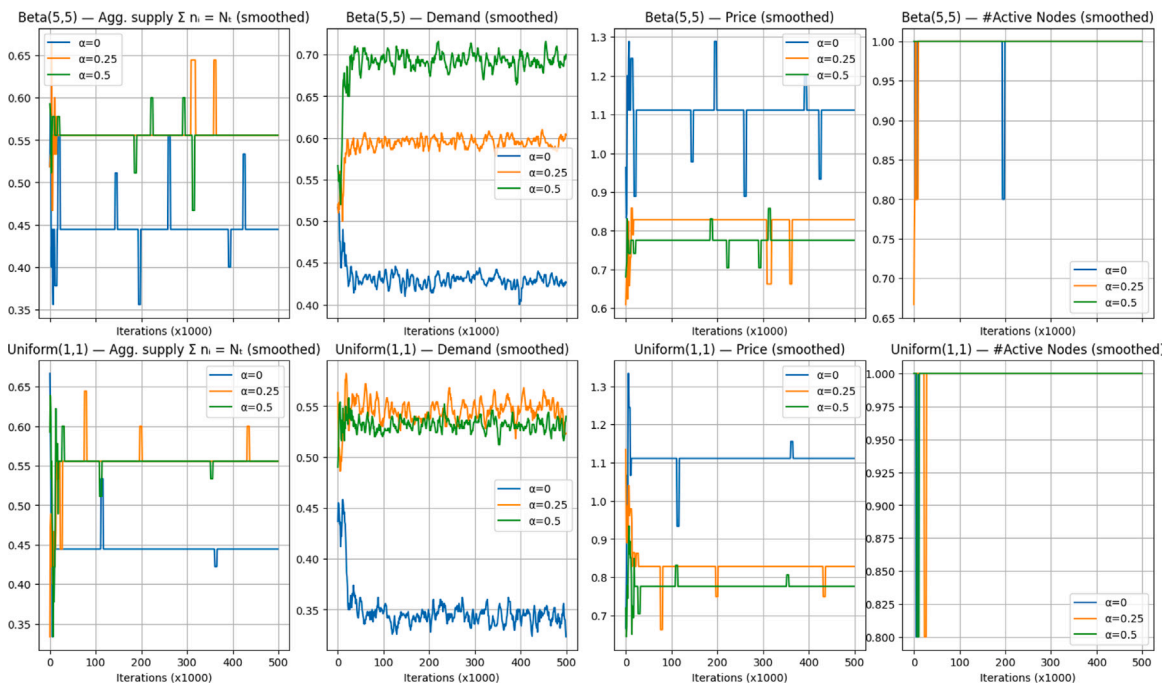


Fig. 2. Results under Monopoly ($K = 1$). 500,000 iterations.

grows, demand is $\approx 0.85-0.95$, and price drops. The number of active firms ranges between 12 and 15 (i.e., 60–75% participation). Figure D.5 in Appendix D shows that α 's influence notably rises with higher entry costs.

To simulate the DePIN Network, using 100 users and providers. Fig. 4 shows that aggregate supply quickly converges to $\approx 0.75-0.79$, with minimal variation across α . The simulation reinforces that decentralized networks can indeed provide high levels of coverage, even with weak network effects. Under DePIN, demand nears 1.0 in all cases. Prices drop sharply to a stable low of

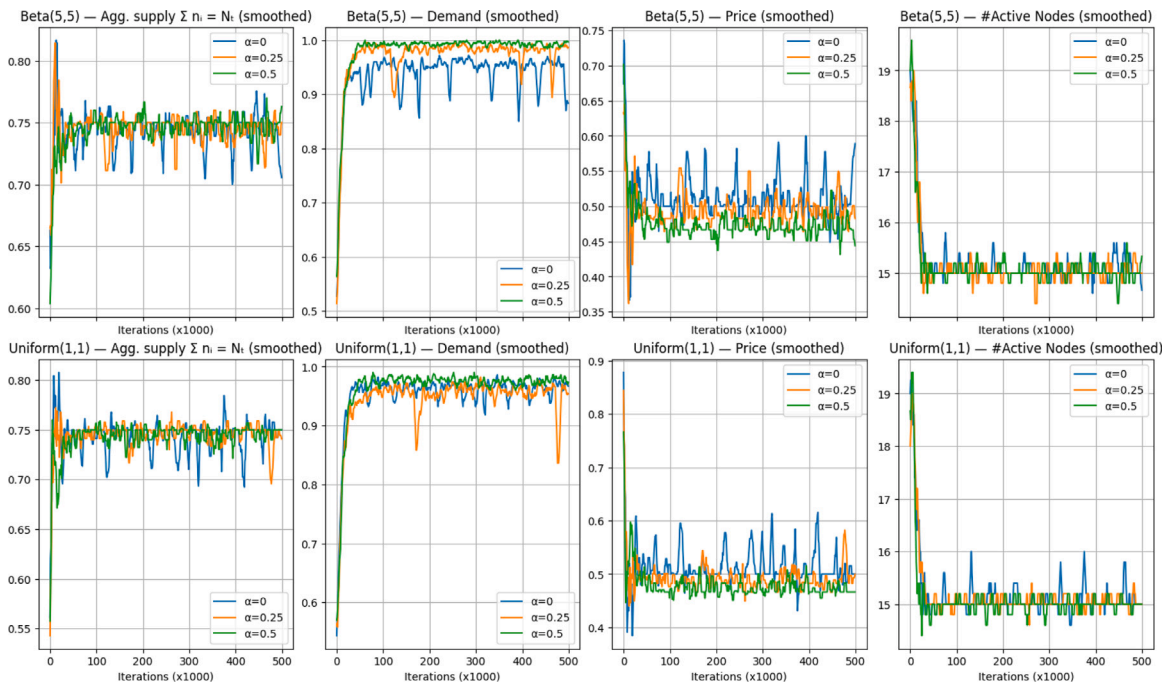


Fig. 3. Simulation under Oligopoly ($K = 20$). 500,000 iterations.

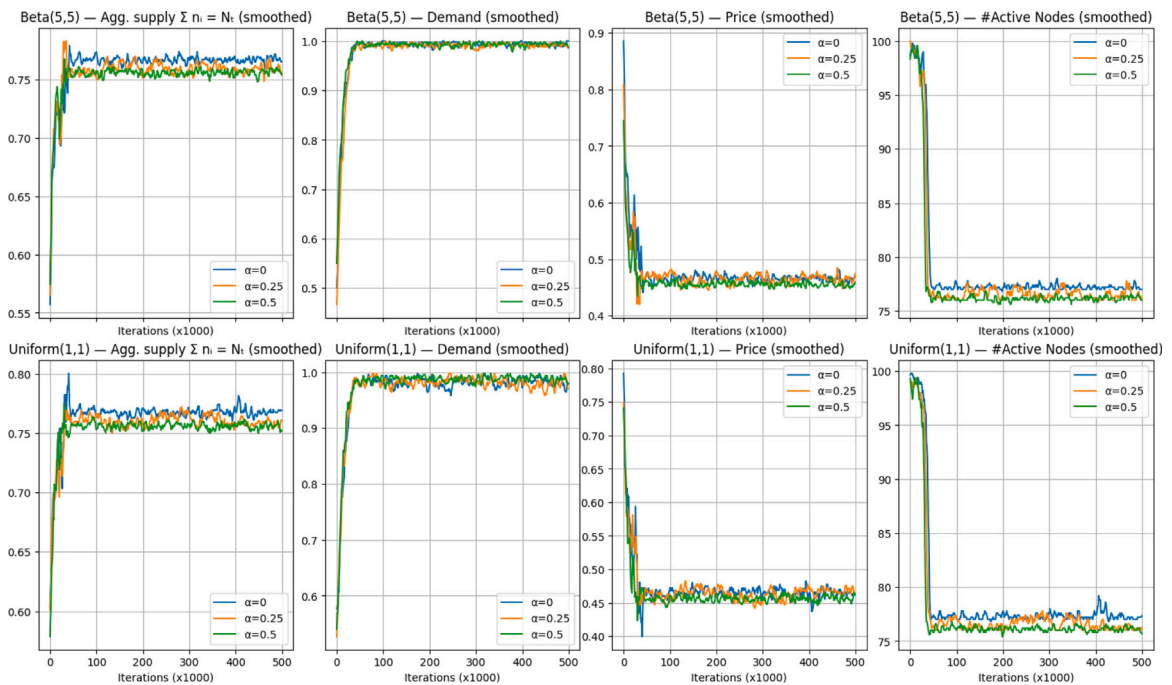


Fig. 4. Simulation under DePIN ($K = 100$). 500,000 iterations.

≈ 0.45 , largely insensitive to α . Active firms stabilize at 75–78%, showing slight attrition but sustained high participation. These outcomes reflect competition driving output close to capacity, prices toward marginal cost, and demand to saturation.

Our multi-agent Q-learning simulations reflect our model’s insights: monopoly yields restricted supply, high prices, and unmet demand. Competition leads to higher supply, lower price, and full demand. This is in line with standard economic theory, and

gives ground for the results in the next section, where we propose an innovative way to achieve Social Optimum in a decentralized manner.

4. Social optimum via DAO

A Decentralized Autonomous Organization (DAO) is a blockchain-native governance institution where membership, voting procedures, and control are specified and enforced through smart contracts. Decisions are taken collectively in a distributed way. Appendix A.3 provides a general presentation about tokenization and governance in decentralized protocols. In this section, we provide a model to implement Social Optimum Coverage for a DAO providing a DePIN.

Following Eq. (17), the planner's first-order condition with fulfilled expectations is

$$p(N, N) + \int_0^N \frac{\partial p(x, N)}{\partial N} dx - c = 0,$$

where $\int_0^N \frac{\partial p(x, N)}{\partial N} dx$ is the positive network externality. A DAO can implement a mechanism to internalize it. At period t , it estimates the externality term

$$E_t := \int_0^{N_t} \frac{\partial p(x, N_t)}{\partial N_t} dx \quad (22)$$

and pays reward $s_t := E_t$, so that producers receive $P_{p,t} = P_{c,t} + s_t$ per unit, where $P_{c,t}$ is the price paid by users. The lump-sum access fee A_t per active user to fund s_t and a per-node rebate R_t that co-funds \mathbb{I} is given by

$$A_t Q_t = s_t N_t + R_t K_t \quad (23)$$

The access fee A_t is non-distortionary at the margin (lump-sum conditional on participation), while s_t changes the marginal condition faced by suppliers. The per-node rebate $R_t \in [0, \mathbb{I}]$ dilutes the fixed burden, thus expanding K_t .

Proposition 5 (*First-best Implementation in the Competitive Limit*). *Under this mechanism with $s_t = E_t$ and price-taking behaviour, the competitive equilibrium implements the planner's allocation. Specifically, at any period t , $P_{c,t} = p(N_t, N_t)$, $P_{p,t} = P_{c,t} + s_t$, $P_{p,t} = c$ jointly imply $p(N_t, N_t) + s_t - c = 0$. With $s_t = E_t$ this is identical to (17); hence $N_t = N^*$, the planner solution.*

Proof in Appendix C.4.

The mechanism is budget-balanced and feasible. If $Q_t = N_t$ and the DAO sets the access fee $A_t = s_t + \frac{R_t K_t}{N_t}$, then (23) holds. As N_t rises, the per-user share $\frac{R_t K_t}{N_t}$ falls, i.e., the fixed burden \mathbb{I} is diluted across a growing user base.

When participants consume and supply, they internalize a share of the benefit through consumption and a share through production rewards. The DAO treasury (funded via A_t , optional fees, or token issuance) redistributes surplus. Heavier support R_t accelerates K_t and helps coordinate on the high-coverage equilibrium. R_t decays as \mathbb{I} is amortized and N_t grows. The effect aligns with the simulation in Section 3.

A DePIN can collect real-time data on usage, willingness to pay, and coverage to estimate the First Best allocation (Eq. (17)) and its positive externality (Eq. (22)). This Social Optimum Pareto-dominates all feasible alternatives (Arrow and Debreu, 1954). Smart contracts distribute gains from any Pareto improvement, assigning rights over the externality. By the Coase theorem, this allows a DAO to implement the allocation in a decentralized way (Coase, 2013). Proposition 5 formalizes how this mechanism achieves a budget-balanced First Best outcome. Appendix E outlines its practical implementation for optimal DePIN provision.

5. Conclusion

This paper develops an economic framework for Decentralized Physical Infrastructure Networks (DePIN), positioning them as a blockchain-based market mode of infrastructure provision. Modelling provider entry through a network-effects framework and multi-agent simulations, we capture producer–user strategic interactions in markets and show how DAO token incentives can align decentralized outcomes with socially optimal benchmarks, characterizing the conditions under which decentralized infrastructure provision emerges and is sustained in equilibrium.

We present four theoretical results. First, we derive the minimum viable coverage level below which market entry is not individually rational as a function of fixed investment costs and token price (Proposition 2). Second, we demonstrate that network externalities induce path dependence, implying that early-stage interventions (e.g., subsidies or token stabilization) lead to higher coverage and welfare (Proposition 4 and Section 4). Third, we benchmark decentralized outcomes against monopoly and oligopolies, showing that it substantially mitigates welfare inefficiencies, moving outcomes toward competitive equilibrium and coordinating high-coverage branch (Proposition 4). Fourth, via a DAO budget-balanced mechanism, DePIN can achieve Social Optimum coverage outcomes in the competitive limit (Proposition 5).

These results are validated through a Q-learning simulation (Section 3). The experiment confirms DePIN supports higher coverage, lower prices, and near-full adoption compared to monopoly or oligopoly structures.

Our findings bridge Tokenomics, Decentralized Finance, and Industrial Organization, embedding rationality into blockchain coordination. They provide a basis for assessing DePIN performance and financial viability, guiding implementation. The framework has been validated in markets (Propositions 3, 4) and identifies conditions for long-term scalability and sustainability in decentralized

infrastructure provision ([Proposition 2](#)). It also offers a transferable methodology. Future research could extend the framework to include heterogeneous demand, layered architectures, network effects, or DAO governance.

This work contributes to the finance literature on decentralized systems and establishes a basis for evaluating the economic viability of Decentralized Physical Infrastructure Networks.

CRedit authorship contribution statement

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Appendix A. Essential functioning of decentralized physical infrastructure networks (DePIN)

The collaborative economy was boosted by the arrival of digital aggregator platforms, which centralised the marketing of similar products, including resources offered by individuals, such as accommodation or transport ([Ghosh and Gorai, 2024](#)). Although they decentralised supply, they concentrated management, control and technical infrastructure, centralising value capture in a single entity. DePIN constitutes a natural extension of the original collaborative economy model, replacing centralised infrastructure provision with contributions from decentralised participants, some of whom are also consumers (prosumers, i.e., producer-consumers), who supply resources to the DePIN network incentivised through tokens.

This integrated intersection of physical networks, blockchain, and tokenized incentives is what we will use to briefly explain the essential functioning of DePIN networks.

A.1. The physical infrastructure layer: Devices and resources

The foundation of each DePIN network lies in physical nodes contributed by participants, which collectively constitute the infrastructure for delivering decentralized services. These nodes may include sensors, routers, GPUs, storage devices, or energy assets such as solar panels. Users contribute resources or surplus capacity, which the network organizes through decentralized protocols according to service type—e.g., storage, connectivity, or energy. More advanced configurations may integrate multiple services or involve both individuals and companies contributing physical infrastructure simultaneously.

Such infrastructures typically fall into two main categories. The first comprises *Physical Resource Networks* (PRNs), formed by tangible, location-dependent hardware—such as sensors, wireless access points, charging stations, or mobility devices—whose value is determined by their physical placement and specific features (e.g., an urban surveillance camera differs in value from one located in a remote area). The second type, *Digital Resource Networks* (DRNs), consists of location-independent digital resources—such as computing power or bandwidth—whose value depends on performance characteristics like capacity or availability, and which are often interchangeable when meeting equivalent specifications.

A.2. Blockchain, smart contracts, and security in DePIN

Blockchain, as a technology based on optimal verification protocols ([Narayanan et al., 2016](#)), enables DePIN to function as transparent, secure, and tamper-resistant systems ([Liu and Omote, 2025](#); [Almadani et al., 2023](#)). Its ability to create an immutable record of operations prevents the alteration of agreements or actions within the network, as block-based verification makes rewriting history difficult. Data integrity is critical in the management of decentralized physical infrastructures. Verification systems promote honest behaviour, enhance resilience against malicious actors, and foster trust among participants. To verify contributions and ensure service quality, DePIN employ specialized blockchain-based consensus mechanisms, such as *Proof of Physical Work* (PoPW), which demonstrate that a node has made a useful and measurable physical contribution.

Proof of Physical Work (PoPW) does not refer to a single protocol, but rather to a category that encompasses proofs adapted to physical environments. These include *Proof of Coverage* (PoC), used by some networks to validate the location and coverage of nodes, or *Proof of Location* (PoL) for geographical verification. Similarly, *Proof of Mobility* (Drive-to-Earn) is used, for example, to reward mobile nodes that collect data. Or *Proof of Rendering Capacity*, implemented to validate computational resources. These proofs vary depending on the network and the physical environment considered, and not all systems implement every modality.

Smart contracts are essential in this layer, functioning as self-executing agreements with coded terms. They automate conditions, eliminate intermediaries, and ensure efficiency and reliability ([John et al., 2023](#); [Cong and He, 2019](#)). In DePIN, they enable data exchange, resource allocation, transaction verification, and reward distribution without third-party intervention. [Table A.2](#) summarizes their main functions:

Table A.2

Key functions and applications of smart contracts in DePIN.

Key function	Description and application in DePIN
Automated Payments and Incentives	Automatically distribute token rewards to contributors and process real-time payments for services rendered.
Resource Allocation and Management	Enable interaction between physical assets and automate tasks such as resource allocation, data exchange, maintenance operations, or resource reassignment.
Decentralized Governance	Facilitate decentralized decision-making through verifiable agreements, voting mechanisms, or distribution of decision-making power.
Service Level Agreement (SLA) Enforcement	Monitor service performance, applying penalties or making adjustments according to agreed service levels.
Data Integrity and Verification	Record and verify transactions and resource contributions, ensuring transparency and data immutability.

Despite the sophistication of these mechanisms, DePIN face structural challenges in security and economic sustainability. Two key attacks stand out, although other vectors may also emerge: *data spoofing*, which falsifies data to obtain rewards without providing services (Liu and Omote, 2025), and *self-dealing*, where a provider acts as a client through fake identities or Sybil attacks to validate their own services or concentrate governance power (Caprolu et al., 2025; Sarkar, 2023).

These vulnerabilities are inherent to the *contribute-to-earn* model, which encourages participation but may promote opportunism. To counteract them, defences include node cross-verification, cryptographic location proofs, reputation systems, and distributed physical observers. Randomized task assignments and access controls also prevent manipulation. Many DePIN projects seek *Byzantine Fault Tolerance* (BFT) to ensure correct operation despite malicious nodes (Milionis et al., 2025). Therefore, incentives align rewards with integrity, since those who can compromise the system the most are the ones who have the most to lose (Savolainen and Soria, 2019).

Technical solutions are complemented by economic mechanisms like *staking* and *slashing*. *Staking* locks tokens as collateral for node operation or data validation, aligning incentives with network performance. *Slashing* penalizes fraud, inactivity, or poor performance by forfeiting part of the stake. For instance, some networks reduce rewards if GPU nodes fail minimum availability or underperform relative to declarations.

A.3. Tokenized economy and decentralized governance in DePIN

A token is a digital asset that represents a set of rights associated with behaviours within the blockchain ecosystem (Treiblmaier, 2023). In DePIN systems, tokens fulfil essential functions: they incentivize, coordinate, and govern participation (Treiblmaier, 2023).

First, tokens serve as payments for those who contribute physical resources, thus promoting the long-term sustainability of the network, following the *contribute-to-earn* model. The reward system is based on each participant's proportional contribution, according to variables such as quantity, quality, uptime, or the characteristics of the resources provided and shared. A well-designed algorithm is crucial to encourage desired behaviours, including expansion into new or underserved areas.

Tokens also confer voting rights, enabling decentralized governance via Decentralized Autonomous Organizations (DAOs) managed by smart contracts automating decision-making. Polkadot's OpenGov exemplifies on-chain proposals and voting, ensuring transparency, community involvement, and immutability. Token holders decide on updates, fees, and funds, aligning management with participant interests.

DePIN governance mechanisms draw on models from digital economy organizations, incorporating systems such as *quadratic voting*, which imposes quadratic costs to reduce the influence of large token holders and promote fairness (de Lima and Oliveira, 2024; Dimitri, 2022). The *liquid democracy* model enables flexible delegation of voting power (Hassan et al., 2022), while *vote-escrowed* or *time-locked voting* mechanisms enhance governance stability by requiring tokens to be locked for a defined period. In addition, DePIN architectures may implement modular governance through sub-DAOs, allowing specific network segments or service layers to be governed independently, thereby improving scalability, adaptability, and alignment with local conditions.

However, the structural dependence on the token can generate problems (Yousaf and Yarovaya, 2022), as declines in its value reduce incentives for participants (Chen et al., 2023), potentially leading to node abandonment and the weakening of physical infrastructure (Liu and Omote, 2025). To mitigate these risks, many DePIN projects implement *vesting schedules*, which gradually distribute the allocated tokens. This prevents their immediate liquidity in large volumes, reduces the pressure from mass sell-offs, and fosters long-term commitment by linking rewards to the sustained success of the ecosystem.

Altogether, the tokenized economy and decentralized governance form an interdependent system linking incentives and governance.

Appendix B. Real-world DePIN applications

The versatility of the DePIN model supports its adoption across multiple sectors in response to the demand for physical infrastructures organized in innovative ways. Although still emerging, its evolution allows for the identification of categories that have been grouped as follows:

- **Computing Networks** (Render, Golem, Akash): aggregate distributed CPUs and GPUs for on-demand computing, including rendering, AI, and edge computing.

Table B.3

DePIN projects capitalization by category.

Source: Authors' elaboration based on data from DePINHub (project counts) and CoinGecko and CoinMarketCap (market caps), accessed July 2025. B = billions, M = millions (USD).

Category	Cap Jul 2024	Cap Jul 2025	Δ Cap	Proj. 2024	Proj. 2025	Δ Proj.	Key Examples	Use Cases
Computing Networks	\$7.5 B	\$9.1 B	+21.3%	28	43	+15	Render, Golem, Akash, Bittensor	GPU render; cloud compute; AI; decentralized training
Storage Networks	\$2.6 B	\$2.8 B	+7.7%	24	30	+6	Filecoin, Storj, Arweave, Shadow	P2P data storage; permanent archive; decentralized cloud
Wireless Connection	\$620 M	\$783 M	+26.3%	15	20	+5	Helium, Nodle, World Mobile	IoT connectivity; 5G access; public Wi-Fi
Mobility, geo and mapping	\$320 M	\$370 M	+15.6%	7	10	+3	Hivemapper, DIMO, GeoDNet, XYO	Crowdsourced mapping; EV data tokens; geolocation
Sensor Networks	\$250 M	\$307 M	+22.8%	16	22	+6	WeatherXM, PlanetWatch, Silencio	Environmental data; geolocation; smart infrastructure
Energy Networks	\$80 M	\$99 M	+23.8%	10	13	+3	PowerLedger, Energy Web, Chain4Energy	P2P energy trading; EV charging grid; green certificates
Total	\$11.37 B	\$13.46 B	+18.4%	100	138	+38	—	

- **Storage Networks** (Filecoin, Arweave, Storj): users contribute disk space as an alternative to centralized cloud solutions. Include, for instance, permanent archiving, distributed backup, and cyclical storage.
- **Wireless Connection** (Helium, Nodle, World Mobile): community hotspot networks offering IoT, 5G, and public Wi-Fi connectivity. Use cases are rural coverage, community Wi-Fi, and decentralized MVNOs.
- **Sensor and Geospatial Networks** (WeatherXM, XYO, PlanetWatch): capture physical and geolocated data for environmental monitoring and spatial analysis; Some subcases could be weather stations, air quality monitoring or asset geolocation.
- **Mobility and Geosocial Networks** (Hivemapper, DIMO, GeoDNet): community networks using dashcams, vehicular, and mobile data for collaborative mapping and vehicular intelligence. The subcases are, for example, dashcam mapping, automotive telemetry or community EV charging infrastructure.
- **Energy Networks** (PowerLedger, Energy Web, Penomo): decentralized energy management applied to P2P trading, renewable microgrids, and electric vehicle charging.

We present the active DePIN projects and the market capitalization as of the date of the analysis. Capitalization estimates a project's value by multiplying token price and supply.

The goal is not only to present data (Lin et al., 2025), but to offer a snapshot of the level of consolidation, dynamism, and strategic attractiveness of each category, reflecting their capacity to scale and generate commercial value. Table B.3 summarizes this analysis, ranking the categories by maturity and representative examples.

According to capitalization data and active projects, *Computing Networks* clearly lead the DePIN space, followed by *Storage Networks* and *Wireless Connectivity*, with more modest values. *Sensor and Geospatial*, *Mobility Geosocial*, and *Energy Networks* show lower capitalization and fewer projects, but their growing dynamism could turn them into strategic areas with high expansion potential.

The DePIN market is dynamic and evolving. It is likely that new categories will emerge, driven by advances in blockchain technology and unmet needs in centralized infrastructures, such as those related to space infrastructure (satellites, telescopes, communications), biotechnology (distributed computing for genomic data), robotics and automation (autonomous fleets in logistics or manufacturing), and water or waste infrastructure (smart water management and recycling).

The table also reports annual growth in capitalization and project count, offering a dynamic perspective of the ecosystem's expansion. While total capitalization grew by about 18%, the number of projects increased by nearly 40%, suggesting that growth is mainly driven by the entry of new, smaller-scale initiatives rather than by large revaluations of existing tokens. This pattern is typical of early-stage, rapidly diversifying sectors, where experimentation and network effects precede large-scale consolidation (Bohnsack et al., 2024; Jacobides et al., 2018; Uche-Soria et al., 2025).

Appendix C. Proofs

C.1. Proof of Proposition 1

Using Eq. (9) and $q(0) = 1$, as $N \downarrow 0$,

$$\frac{dp}{dN} \sim \begin{cases} +\infty & \text{if } \alpha < 1, \\ \eta - \frac{\phi}{f(1)} & \text{if } \alpha = 1, \end{cases} \tag{C.1}$$

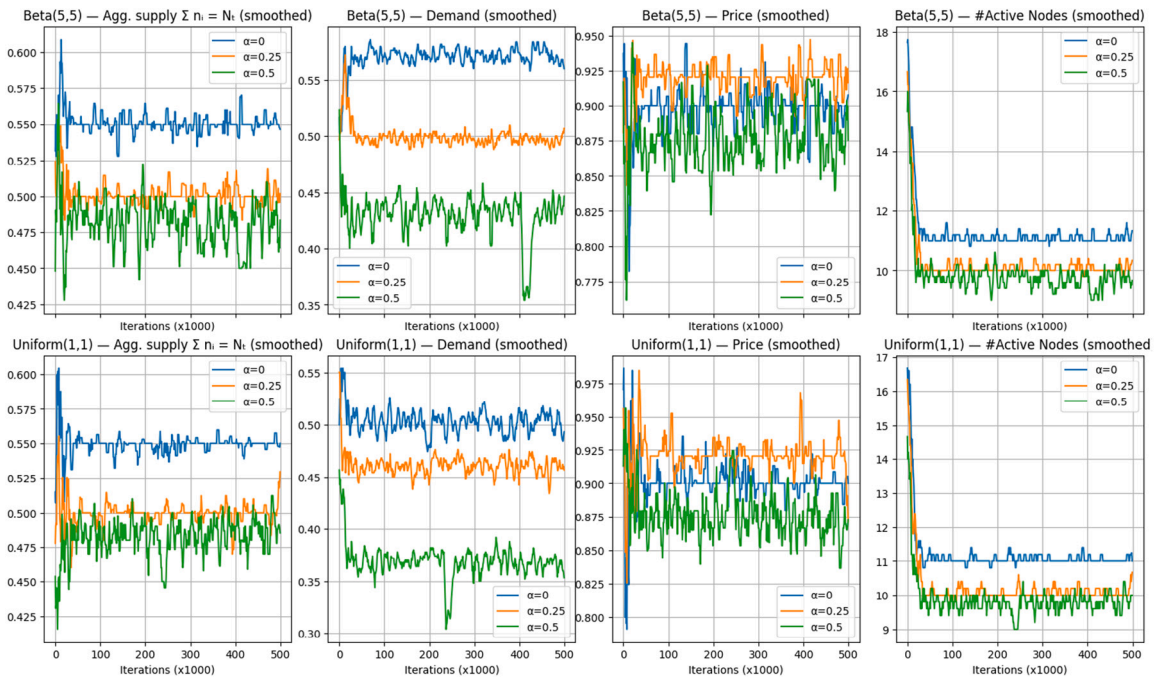


Fig. D.5. Oligopoly simulation with doubled entry cost per firm.

so the slope is positive under the stated conditions. As $N \uparrow 1$, $q(N) \rightarrow 0$ and $q'(N) = -1/f(q(N))$ stays finite and negative; the second term of (9) dominates, yielding $\frac{dp}{dN} < 0$. By continuity, there is at least one turning point; strict quasi-concavity of $p(\cdot, \cdot)$ here gives uniqueness. \square

C.2. Proof of Proposition 2

Any interior monopoly choice must lie on the decreasing branch $N \geq N_{\text{peak}}$ and satisfy $N[p(N, N) - c] \geq \mathbb{I}$. The smallest such N is N_{min} . If N_{min} doesn't cover the entry costs \mathbb{I} then $N_t = 0$ and there is no coverage provided by the monopoly. \square

C.3. Proof of Proposition 4

Non-monotonicity implies two intersections with the horizontal line at c : one on each side of N_{peak} . By Proposition 1, the monopoly's interior choice must be on the decreasing branch ($N^M \geq N_{\text{peak}}$). If $N^M[p(N^M, N^M) - c] < \mathbb{I}$, provision is not incentive compatible and $N = 0$ is optimal.

On the other hand, allowing arbitrarily small n_j lets agents cover fraction \mathbf{I} of \mathbb{I} and the residual fixed cost per node falls, making entry profitable for a larger set of agents. Thus, K weakly increases. Taking $K \rightarrow \infty$ in (13) yields $p(N^C, N^C) = c$. For K large enough, the markup term in (13) diminishes and the realized N must be near a solution to $p(N, N) = c$, i.e., either N_ℓ or N_h . By Proposition 1, to operate, agents must cover \mathbf{I} from variable margins. Because $p(N, N)$ is decreasing for $N \geq N_{\text{peak}}$, the per-unit margin is larger in the neighbourhood of N_h than at N_ℓ , and co-funding of \mathbb{I} further relaxes the viability constraint at higher N . Hence, N_h is selected. \square

C.4. Proof of Proposition 5

In the competitive limit, each producer is a price taker and supplies until $P_{p,t} = c$. Users face $P_{c,t}$ and demand $Q_t = N_t$ such that $P_{c,t} = p(N_t, N_t)$. The per-unit subsidy raises producers' marginal revenue to $P_{p,t} = p(N_t, N_t) + s_t$. Setting $s_t = E_t$ aligns the decentralized marginal condition with the planner's FOC. \square

Appendix D. Summary of simulation results and effect of higher entry costs on equilibrium coverage

Fig. D.5 presents a simulation for the oligopoly case, showing that the influence of α increases substantially when the entry cost per firm is doubled. Table D.4 presents the main simulation statistics for the different valuation distributions, types of competition, and values of α .

Table D.4
Summary of simulation statistics by scenario, distribution and α .

Distribution	α	Supply		Demand		Price	
		Mean	σ	Mean	σ	Mean	σ
(a) DePIN 100 prosumers							
Beta(5,5)	0.0000	0.7621	0.0260	0.9825	0.0575	0.4759	0.0519
	0.2500	0.7561	0.0236	0.9782	0.0641	0.4712	0.0425
	0.5000	0.7530	0.0203	0.9838	0.0499	0.4611	0.0332
Uniform(1,1)	0.0000	0.7640	0.0223	0.9703	0.0571	0.4720	0.0446
	0.2500	0.7567	0.0209	0.9704	0.0576	0.4701	0.0381
	0.5000	0.7528	0.0218	0.9765	0.0563	0.4615	0.0358
(b) Monopoly							
Beta(5,5)	0.0000	0.4467	0.0604	0.4308	0.0182	1.1067	0.1208
	0.2500	0.5578	0.0579	0.5930	0.0187	0.8205	0.0855
	0.5000	0.5558	0.0326	0.6893	0.0282	0.7744	0.0435
Uniform(1,1)	0.0000	0.4456	0.0458	0.3485	0.0256	1.1089	0.0916
	0.2500	0.5527	0.0546	0.5456	0.0198	0.8299	0.0749
	0.5000	0.5538	0.0455	0.5316	0.0174	0.7759	0.0547
(c) Oligopoly, 20 providers							
Beta(5,5)	0.0000	0.7409	0.0308	0.9434	0.0530	0.5181	0.0617
	0.2500	0.7416	0.0268	0.9562	0.0564	0.4978	0.0485
	0.5000	0.7429	0.0257	0.9810	0.0530	0.4782	0.0425
Uniform(1,1)	0.0000	0.7429	0.0268	0.9145	0.0549	0.5143	0.0536
	0.2500	0.7445	0.0264	0.9462	0.0522	0.4926	0.0478
	0.5000	0.7410	0.0276	0.9717	0.0516	0.4814	0.0451
(d) Oligopoly, 20 providers, double entry cost							
Beta(5,5)	0.0000	0.5510	0.0197	0.5701	0.0151	0.8981	0.0394
	0.2500	0.5012	0.0190	0.4992	0.0158	0.9183	0.0314
	0.5000	0.4819	0.0310	0.4299	0.0269	0.8769	0.0408
Uniform(1,1)	0.0000	0.5495	0.0198	0.5032	0.0200	0.9010	0.0396
	0.2500	0.4997	0.0189	0.4612	0.0171	0.9208	0.0312
	0.5000	0.4825	0.0291	0.3691	0.0213	0.8762	0.0376

Appendix E. Sketch of a potential DAO mechanism

(i) Externality Estimation.

Using $p(N, N) = (\phi + \eta N^\alpha)F^{-1}(1 - N)$,

$$\frac{\partial p(x, N)}{\partial N} = \eta \alpha N^{\alpha-1} F^{-1}(1 - x) - \frac{\phi + \eta N^\alpha}{f(F^{-1}(1 - x))}, \tag{E.1}$$

and the DAO computes

$$E_t = \int_0^{N_t} \frac{\partial p(x, N_t)}{\partial N_t} dx, \tag{E.2}$$

possibly via an online estimator with smoothing, e.g.,

$$s_{t+1} = \beta s_t + (1 - \beta) \widehat{E}_t, \quad \beta \in [0, 1). \tag{E.3}$$

(ii) Rewards & Verification.

Each provider j receives

$$\text{payout}_j = n_{j,t} s_t + R_t \cdot \mathbf{1}\{n_{j,t} > 0\}, \tag{E.4}$$

conditional on cryptographic proofs (e.g., location/quality oracles) and subject to slashing for misreports.

(iii) Governance and Consensus.

A DAO chooses (s_t, R_t, A_t) to maximize an on-chain proxy for welfare,

$$\max_{s_t, R_t, A_t} \widehat{W}_t = \widehat{B}(N_t, N_t) - c N_t - \mathbb{I} K_t - \lambda \text{Var}(s_t) \tag{E.5}$$

subject to (23) and bounds on token issuance. Voting can combine stake with usage-based credentials; quadratic voting on R_t helps reflect dispersed user preferences while avoiding plutocracy. In steady state, the DAO targets $s_t \approx E_t$ and the competitive outcome implements the planner allocation by Proposition 5.

Data availability

The file uploaded as Supplementary Material with the name “DePIN python code rep” contains access to the Github repository where the code used in the simulation is hosted.

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