





The DePIN phenomenon: Characteristics, reward architecture, and practical implementations

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ARTICLE INFO

Keywords:

DePIN
Reward mechanisms
Governance
Blockchain
Internet of things

ABSTRACT

Decentralized Physical Infrastructure Networks (DePIN) combine blockchain technology with distributed physical assets to organize and motivate the provision of real-world infrastructure. Although the term emerged in 2022, comprehensive studies on the subject are limited. This study bridges that gap by providing a structured analysis of DePIN. It (1) describes the core features of DePIN, (2) proposes a six-layer reward architecture, and (3) examines the most relevant real-world implementations. Findings indicate a rapid growth from 2022 to 2024, frame DePINs into six main categories and explore 21 active projects, focusing on their open-source communities and evaluating their operability across multiple blockchains.

1. Introduction

Blockchain technology has advanced far beyond digital currency, now serving as the backbone of various decentralized systems driven mainly by smart contracts [1–3]. Originally envisioned as distributed ledgers, blockchains have expanded to support decentralized applications (DApps), Decentralized Autonomous Organizations (DAOs), and other non-transactional services [1]. Smart contracts enable immutability and transparency on-chain activities, reducing the need for trusted intermediaries [1,3]. New fundraising models emerged with Initial Coin Offerings (ICOs), allowing projects and DAOs to raise capital through token sales [2,4]. Notable initiatives such as the DAO demonstrated this approach by successfully raising large funds via decentralized crowdfunding without traditional regulation [4], marking the first large-scale community-driven capital distribution [2].

Afterwards, Decentralized Finance (DeFi) created blockchain-based platforms that provide financial services without intermediaries [1, 3]. DeFi replicates traditional financial products like exchanges, lending, and on-chain investment funds in open, permissionless environments governed by code [3]. Simultaneously, Non-Fungible Tokens (NFTs) introduced unique digital ownership and provenance, opening markets for art, media, and intellectual property while enabling creators to retain royalties [2,5]. The relevance of blockchain extends to supply chain management through DApps that offer traceability and

transparency [6–8]. These establish decentralized networks for secure data exchange, automatic provenance tracking, and faster supply chain operations through IoT-enabled sensors [6,8].

More recently, Decentralized Physical Infrastructure Networks (DePINs) have emerged in Web3, leveraging blockchain, IoT, and tokenomics to incentivize grassroots construction of physical infrastructure [9–11]. Contributors provide resources like storage, processing, wireless communication, or sensor data to create decentralized alternatives to centralized solutions [11–13]. For instance, Helium rewards hotspot owners with HNT tokens for LoRaWAN and 5G coverage through a Proof-of-Coverage (PoC) protocol [11], while Filecoin compensates contributors for storage capacity and duration [12]. These networks employ cryptographic validation and token incentives to build autonomous, community-owned infrastructure [9,11].

DePINs utilize blockchain-based reward schemes to simplify deployment and upkeep, linking incentives to performance and reliability [9, 12,14]. This promotes shared ownership, extensive participation, and resilience compared to centralized systems [11]. Integrating IoT and blockchain enhances privacy, traceability, and security while reducing operational costs [7]. Although research on DePINs remains limited [11,15], interest has increased as adoption expands [9,16]. Market capitalization grew from \$3.1 billion to \$11.8 billion between April 2023 and March 2024 [9]. Early studies highlight governance structures, token incentives, and protocol standardization, often utilizing

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<https://doi.org/10.1016/j.ict.2026.02.005>

Received 25 July 2025; Received in revised form 21 December 2025; Accepted 5 February 2026

Available online 5 February 2026

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DAOs for decision-making [1,9,14]. These initial efforts lay the foundation for more in-depth research into DePIN architectures, consensus algorithms, reward systems, and performance [11,15].

This study examines DePIN systems from technical and economic perspectives. Although individual components have been studied in isolation, this paper offers, to our knowledge, the first structured account connecting architectural design with operational and market behavior across a diverse set of projects.

The research is guided by three questions, each addressing a different aspect of the DePIN ecosystem:

RQ1: What are the main characteristics of the DePIN phenomenon?

This question aims to clarify how DePIN differs from earlier blockchain applications and to identify the core elements that define it as a distinct infrastructural model.

RQ2: What is the general architecture of a DePIN reward system?

Here, we examine how DePINs structure their incentive mechanisms, with the goal of identifying recurring design patterns that support Decentralized coordination of physical resources.

RQ3: How are DePIN projects composed in practice?

This question investigates how the conceptual model is implemented across real-world systems, focusing on project composition, operational metrics, and technological choices.

To address these, we provide a definition of DePIN and identify six key categories of projects: computing, storage, wireless, sensors, bandwidth, and AI. We present a six-layer reward architecture observed across projects and analyze a selection of real-world implementations. The analysis includes blockchain use, reward models, open-source activity, and geographical distribution.

The study traces DePIN development from its early links to blockchain and IoT (e.g., Filecoin, Helium) around 2013, to its formal recognition in 2022. It also examines layered reward systems, including cryptographic verification, blockchain consensus, token distribution, and participant incentives. In addition to technical aspects, we include quantitative analysis of network adoption, market activity, and open-source engagement. We also consider broader implications for infrastructure access, community participation, and funding mechanisms.

This work is a mixed-methods descriptive study that combines conceptual analysis, architectural modeling, and empirical investigation. It aims to systematize the DePIN phenomenon by defining its principal characteristics, introducing a six-layer reward architecture, and examining data from a curated set of operational projects. The study integrates qualitative synthesis from industry definitions and literature with quantitative data gathered from blockchain explorers, GitHub repositories, and market sources. This approach enables a structural understanding of how DePINs are designed and a practical assessment of how they operate in real-world settings.

The paper is structured as follows. Section 2 introduces the DePIN concept and its global diffusion; Section 3 reviews prior work; Section 4 describes the general architecture and application areas; Section 5 analyses selected projects based on technical and market data; Section 6 discusses open research challenges and future directions; Section 7 addresses threats to validity; and Section 8 concludes the paper.

2. The DePIN phenomenon

We begin by providing a definition of the term DePIN.

Definition 1. DePIN stands for *Decentralized Physical Infrastructure Network* and refers to infrastructure projects that support collaboration among individuals to create and manage their own secure, Decentralized, and verifiable real-world public infrastructure network. These projects use blockchain and Decentralized ledger technology to trace and reward participants with crypto assets when they allocate capital, share underutilized resources, or exchange data within the network.

The definition above captures the main elements that have come to characterize the term in current usage.

DePINs originated from the convergence of blockchain and Internet of Things (IoT) technologies [17]. While blockchain introduced mechanisms for Decentralized coordination and token-based incentives, IoT enabled autonomous data exchange and device-level interaction. Together, these made it possible to develop infrastructure systems that are collectively maintained and verifiably operated without central authority.

Although the term *DePIN* was formalized only recently, the underlying concept can be traced back to early initiatives around 2013, as summarized in Table 1. That year marked the appearance of the first Decentralized, peer-to-peer file storage projects inspired by Bitcoin, establishing the basis for infrastructure networks with Decentralized ownership. Projects such as Filecoin and Golem were early examples in the areas of storage and computation. In subsequent years, platforms like Power Ledger, Arweave, and Fetch.ai expanded these ideas to energy markets and device-level coordination in IoT. By 2019, bandwidth-sharing networks such as Helium introduced token-based wireless infrastructure models, using incentives similar to those in blockchain mining.

Initially, these projects developed independently, each addressing specific aspects of Decentralized infrastructure. In 2021, *IoTeX* introduced the concept of *MachineFi*, which framed machine-driven economies in financial terms using blockchain. By 2022, new frameworks such as Proof of Physical Work (PoPW), Token Incentivized Physical Networks (TIPIN), and EdgeFi added further structure to Decentralized infrastructure models. That same year, Bittensor was launched and later became one of the most prominent DePIN initiatives.

The term *DePIN* was introduced in November 2022, when the research firm *Messari* conducted a public *Twitterpoll* to establish a common term for this category of systems. Table 2 lists reference websites and platforms that track and analyze the evolving DePIN ecosystem.

At the same time, Messari formally defined DePIN as networks that use crypto-based incentives to coordinate the deployment and maintenance of essential infrastructure on public blockchains. Their 2023 report expanded this definition, presenting DePIN as a unified model comprising Decentralized hardware, off-chain computation, token incentives, and distributed governance. This marked a shift from isolated experimental efforts to a more coordinated approach aimed at building scalable, community-based infrastructure systems.

The term DePIN is now widely adopted by projects seeking to align with market trends and attract investment. Many earlier blockchain infrastructure initiatives have adopted the label retrospectively, suggesting that DePIN functions partly as a marketing term rather than a strictly technical one. This reflects a broader pattern in the blockchain sector, where new terminology is frequently used to rebrand existing concepts. As a result, reliance on self-applied DePIN labels may blur the distinction between substantive developments and strategic repositioning.

2.1. Sources of definitions

This subsection reviews how the term *DePIN* has been defined by key organizations and projects in the blockchain ecosystem. To develop a consistent working definition, we analyzed descriptions from widely recognized sources: Messari, Binance, DePIN Pulse (formerly DePIN Ninja), IoTeX/DePIN Scan, and the documentation of two notable DePIN projects, Helium and Phantom.

Table 1
Evolution of decentralized physical infrastructure networks (DePIN).

Year	Project	Category	Description	Reference
2013–14	Filecoin	Storage Project	Conceptualized decentralized storage; mainnet launched in 2020	ProtocolLabs
2013	Helium	Wireless Project	Blockchain-based IoT network incentivizing hotspots (mainnet: 2019)	HeliumDocs
2014–15	Golem	Computation Project	First decentralized compute network (mainnet: 2018)	GolemNetwork
2016	PowerLedger	Energy Project	Peer-to-peer renewable energy trading platform (mainnet: 2017)	PowerLedger
2017	Arweave	Storage Project	Permanent data storage protocol (mainnet: 2018)	Arweave
2017	Fetch.ai	AI/IoT Project	Autonomous agents for IoT coordination (mainnet: 2019)	Fetch.ai
2018	Akash Network	Computation Project	Decentralized cloud compute marketplace (mainnet: 2020)	Akash
2019	Bittensor	AI/Computation Project	Decentralized machine-learning network (mainnet: 2021)	Bittensor
2021	MachineFi	Definition	Introduced machine-driven blockchain economies	IoTeX
2022	Poll	Definition	Held poll to standardize sector terminology	Messari
2022	DePIN definition	Definition	First formal mention of DePIN by Messari	Messari
2023	Hivemapper	Mapping Project	Crowdsourced decentralized mapping via dashcam data	Hivemapper

Table 2
Reference websites for DePIN projects.

Website	Purpose	Citation
Messari	Provides comprehensive sector reports and dashboards (State of DePIN 2024)	https://messari.io
DePIN.Ninja	Tracks active devices, revenue, and project performance	https://depin.ninja
CoinGecko	Tracks market data for DePIN tokens (market cap, price trends)	https://www.coingecko.com
DePINscan	Monitors network metrics such as node counts and token distributions	https://depinscan.io
CoinList	Lists top DePIN projects and fundraising rounds (Filecoin)	https://coinlist.co
Coin Market Cap	Monitors market data for cryptocurrencies (global liquidity, volatility)	https://coinmarketcap.com
DePIN Hub	Provides DePIN project analytics and market insights	https://depinhub.io
IoTeX	Provides decentralized physical infrastructure networks (DePIN) solutions	https://iotex.io

Messari Research: *DePIN (Decentralized Physical Infrastructure Networks)* refers to blockchain-powered networks that incentivize individuals and organizations to deploy, operate, and maintain real-world infrastructure (e.g. wireless networks, energy grids, compute resources) through token-based rewards. These networks use crypto-economic mechanisms to coordinate the Decentralized supply and demand for physical services.

Binance Square: *DePIN* refers to infrastructure projects that apply blockchain and crypto-economic models to encourage individuals to contribute capital or under-utilized resources in order to build transparent, Decentralized, and verifiable infrastructure. These projects typically focus on either physical or digital resource networks, operate under shared principles such as collective ownership, and prioritize distributed systems over centralized control.

DePIN Pulse (formerly DePIN Ninja): *DePIN* is described as a global movement that enables individuals to build and maintain public infrastructure. It supports collaboration across sectors such as telecommunications, cloud computing, and renewable energy using blockchain-based incentives.

IoTeX/DePIN Scan: *DePIN* is presented as a community-driven model for deploying and managing physical infrastructure, including wireless networks, energy systems, and IoT devices. Instead of relying on centralized organizations, DePINs allow individuals and organizations to contribute physical assets, such as WiFi hotspots or solar panels, and receive crypto-token rewards.

Helium: According to the [Helium](#) documentation, DePIN projects use Decentralized technologies to support real-world applications such as wireless coverage, mapping, rendering, and transport services. These systems connect people and devices through token incentives and blockchain coordination.

Phantom: As stated in the [Phantom](#) documentation [18], DePIN refers to networks that use crypto tokens and blockchains to develop and operate real-world infrastructure. Unlike corporate-led systems, these networks are owned and maintained by communities through token economies.

Across these sources, a common interpretation emerges: DePIN refers to Decentralized systems that manage and reward the provision of physical infrastructure. Although the language differs, all definitions stress the role of blockchain in enabling coordinated, incentive-based resource sharing beyond traditional ownership models. The definition used in this paper builds on these elements, presenting DePIN as a model of community infrastructure supported by token-based economic incentives.

2.2. The expansion of the DePIN phenomenon

This section examines the growth of the DePIN phenomenon over time, focusing on the number of projects and their estimated value. The data are drawn from several sources, including Messari, DePIN Ninja, DePIN Scan, DePIN Hub, CoinMarketCap, and CoinGecko.

These platforms apply different data collection methods, and results are not always independently verified, which may introduce inconsistencies or biases. However, it is worth noting that DePIN Scan and DePIN Hub focus specifically on projects with a verifiable real-world presence.

As of 2022, Messari reported around 100 DePIN projects. According to the same source, the number increased to approximately 650 in 2023 and 1170 in 2024, although this count does not distinguish between active and inactive projects.

As of 12 June 2025, *DePIN Pulse* (formerly DePIN Ninja) reports a slightly higher figure, listing 2381 projects. This total includes early-stage initiatives and projects that are not yet operational, reflecting the broader expansion of the ecosystem.

In contrast, data from *IoTeX's DePINscan*, also as of 12 June 2025, identifies only 321 projects with verifiable on-chain activity, such as active devices and token transactions. This lower figure reflects a more selective criterion that focuses on networks currently in operation.

The differences between these sources illustrate methodological variation: while Messari and DePIN Pulse account for a broader pipeline of initiatives, DePINscan reports only those with demonstrable deployment and usage. [Table 3](#) shows these contrasts clearly.

Leading DePIN projects. [Fig. 1](#) shows the market capitalization of the 21 leading DePIN projects, based on data compiled from official explorers, DePIN Scan, CoinGecko, CoinMarketCap, and DePIN Ninja. Among these projects, *Bittensor* has the highest valuation at \$3.08 billion, followed by *Filecoin* at \$2.08 billion. *Fetch.ai* and *Render* are also among the top projects, with market values of \$1.85 billion and \$1.73 billion, respectively. Other notable projects include *BitTorrent*, *Helium*, and *Arweave*, all of which continue to contribute to the development of Decentralized infrastructure.

To confirm that these are DePIN projects, we manually verified their presence on specialized websites and reviewed the documentation provided on their official pages. We also checked the blockchain

Table 3
Number of DePIN projects by year.

Year	Number of DePIN projects	Sources	Notes
2022	≤ 100	Messari	Early growth phase, focused on computing and storage.
2023	≤ 650	Messari	Expansion into wireless, energy, and AI.
2024	295 – 1,170	DePINscan, Messari	DePINscan includes only operational projects while Messari includes all types of initiatives (active and developmental)
June 2025	322 – 2,381	DePINscan, Depin Pulse	DePINscan includes only operational projects while DePIN Pulse includes all project initiatives

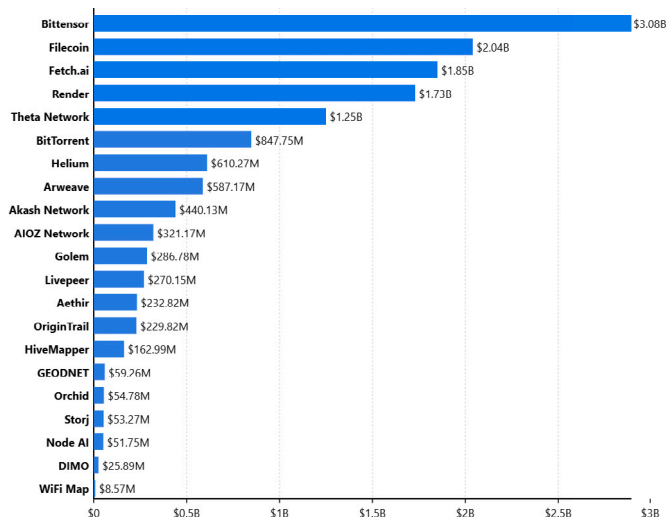


Fig. 1. DePIN top 21 projects by market cap.

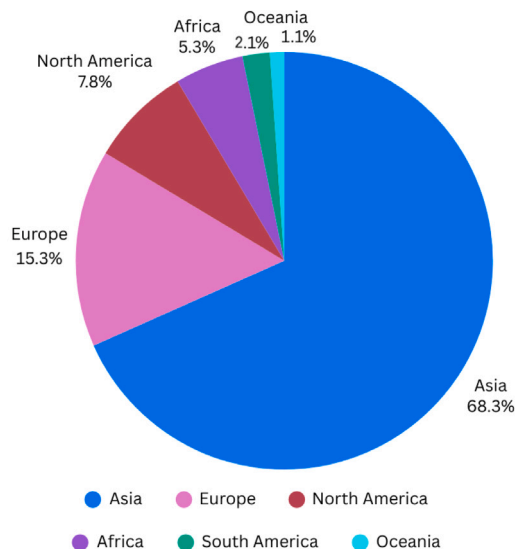


Fig. 2. DePIN Global Device Distribution by Region.

activity associated with each project. Table 4 presents the outcome of this verification process for the 21 selected projects.

While all listed projects appear on major cryptocurrency platforms such as CoinMarketCap and CoinGecko, five are not listed on DePIN Hub, two are missing from DePIN Scan, and one does not appear on DePIN Pulse. Moreover, for ten projects, the term *DePIN* does not explicitly appear in the official documentation. However, these projects meet all the criteria set out in the definitions previously discussed and are marked with an asterisk in the table.

Sector investments. Table 5 presents key investment data for the DePIN sector, based on Messari’s 2024 analysis. The combined market valuation of DePIN-related tokens is estimated at \$50 billion, covering approximately 350 projects in areas such as wireless communication, computing, energy, and sensor networks. Early-stage funding, including pre-seed and seed rounds, accounts for 50.7% of the total investment. Community-based funding mechanisms, such as node sales, liquidity pools, and crowdfunding, have raised \$230 million. These contribute to an estimated \$500 million in annual recurring revenue, largely concentrated among the top 20 projects. Institutional investors have also committed more than \$100 million, with firms such as EV3, Multicoïn, and a16z Crypto each supporting over eight DePIN initiatives.

The geographic distribution of DePIN-connected devices shows clear patterns of regional adoption. Data from DePIN Scan report deployments in nearly 196 countries, indicating widespread international uptake. Asia accounts for the largest share, with approximately 68.5% of devices, followed by Europe (15.2%), North America (7.8%), and smaller proportions in other regions. This distribution points to particularly strong adoption in Asian markets, with a growing presence in other parts of the world.

Fig. 2 presents a regional breakdown of device deployment, highlighting the concentration in Asia and illustrating the global spread of DePIN systems.

As of 12 February 2025, *DePINScan* reports a total of 5,477,931 devices distributed across 196 countries and regions. The associated pie chart shows regional shares, with Asia accounting for 68.5% of deployed devices, followed by Europe (15.2%), North America (7.8%), and other regions comprising the remainder. The estimated market value of these devices is approximately \$4.5 billion.

3. Literature review

A structured literature search was carried out using multiple databases (namely Scopus, Google Scholar, and ResearchGate) to identify academic work on Decentralized Physical Infrastructure Networks. A multivocal approach was adopted to capture a broader range of works in terms of both typology and content.

The first search was conducted on Scopus using the following query:

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(TITLE (DePIN) OR KEY (DePIN) OR ABS ("Decentralized Physical Infrastructure1")) AND (PUBYEAR > 2013)
```

As of 12 June 2025, this search returned 18 records. Full-text access was available for 14 of these; one was in Chinese and excluded, leaving 13 English-language papers, all of which were considered relevant and included in the analysis.

A parallel search was conducted on Google Scholar using the search terms:

Table 4

Presence of the selected project in source websites and verification of on-chain activity. In the Official Website column, the symbol */ indicates that the website documentation describes the project with the main characteristics of a DePIN, but does not explicitly mention this term.

Project	DePIN Hub	DePINscan	Depin Pulse	CoinGecko	CoinMarketCap	Official Website	Onchain activity
Render	✓	✓	✓	✓	✓	✓	✓
Akash Network	✓	✓	✓	✓	✓	✓	✓
Golem	✓	✓	✓	✓	✓	✓	✓
Filecoin	✓	✓	✓	✓	✓	✓	✓
Arweave	✓	✓	✓	✓	✓	*✓	✓
Storj	✓	✓	✓	✓	✓	✓	✓
Helium	✓	✓	✓	✓	✓	✓	✓
WiFi Map	✓	✓	✓	✓	✓	*✓	✓
Bittensor	✓	✓	✓	✓	✓	*✓	✓
Theta Network	✓	✓	×	✓	✓	*✓	✓
Hivemapper	✓	✓	✓	✓	✓	✓	✓
DIMO	✓	✓	✓	✓	✓	*✓	✓
GEODNET	✓	✓	✓	✓	✓	*✓	✓
Aethir	✓	✓	✓	✓	✓	*✓	✓
Livepeer	✓	✓	✓	✓	✓	✓	✓
Orchid	✓	✓	✓	✓	✓	✓	✓
AIOZ Network	×	✓	✓	✓	✓	✓	✓
OriginTrail	×	✓	✓	✓	✓	*✓	✓
Fetch.ai	×	✓	✓	✓	✓	✓	✓
BitTorrent	×	×	✓	✓	✓	*✓	✓
Node AI	×	×	✓	✓	✓	*✓	✓

Table 5

DePIN sector investment overview. Messari 2024 [19].

Metric	Description	Key details	Value
Market valuation	Total market capitalization of DePIN tokens	Covers 350 projects across wireless, compute, energy, and sensor networks	\$50B
Funding allocation	Distribution of private capital by stage	Pre-seed/seed rounds dominate, reflecting high-risk appetite for early-stage infrastructure	50.7%
Community funding	Node sales, liquidity pools, and crowdfunding	Glow Protocol allocated 17% of tokens to liquidity pools; \$190M+ from node sales	\$230M
Revenue generation	Annualized recurring revenue (ARR) from onchain services	Top 20 projects (e.g., Helium, Akash) drive monetization via decentralized wireless and compute	\$500M
Institutional participation	Capital deployed by dedicated DePIN funds	EV3 (\$50M AUM), Multicoins, and a16z Crypto lead with 8+ investments each	\$100M+

DePIN "Decentralized Physical Infrastructure Network "

This search yielded 27 results. Eight of these overlapped with the Scopus set, resulting in 19 unique entries. Of these, 2 full texts were inaccessible and 3 were in languages other than English. After screening the abstracts of the remaining 14 documents, 7 papers were selected. The same procedure was applied on ResearchGate, leading to the retrieval of one additional relevant publication.

In total, 20 publications were selected for review. These include 14 conference papers (one of which is a workshop summary), 2 journal articles, 1 book chapter, and 3 preprints. This set reflects the current level of academic engagement with DePIN and forms the basis for the analysis summarized in Table 6.

It is worth noting that all the papers identified date from 2023 onwards. Furthermore, 2023 saw the first workshop dedicated to DePINs, which was co-located with the IEEE World Forum on Internet of Things [16]. The contributions of the selected papers are discussed below, grouped by type of contribution.

3.1. DePIN surveys and definitions

Several of the reviewed studies focus on defining and structuring the DePIN concept, aligning closely with the aims of this work. A notable example is the survey by Lin et al. [9], which proposes a five-layer hierarchical architecture for DePIN systems. Their model distinguishes between the Application, Governance, Data, Blockchain, and Infrastructure layers. It also categorizes DePIN applications into two main types:

Physical Resource Networks (such as sensor-based and Decentralized wireless systems) and Digital Resource Networks (including computing and storage platforms). This framework offers a structured method for analyzing the diversity of DePIN implementations.

Pillai et al. [12] examined DePINs by studying projects such as Filecoin, Helium, and IoTeX. Their work describes how token incentives support Decentralized physical infrastructures and analyses the role of DePINs in modular layer-2 blockchain ecosystems through detailed case studies.

Ballandies et al. [14] introduced a taxonomy that categorizes DePINs along three dimensions: Distributed Ledger Technology (DLT), crypto-economic design, and physical infrastructure network architecture. Their framework distinguishes between hardware (including devices and ecosystem components) and middleware (such as data access, routing, and computing), thereby providing a standard approach to classify and assess DePIN systems.

Hu et al. [1] contributed to this discussion by proposing a taxonomy for blockchain-based DePINs, classifying them based on dimensions that link technical design with economic incentives. Ratanpara et al. [23] reviewed the literature comparing the capabilities, security challenges, and regulatory contexts of Decentralized and centralized models. In addition, Fan et al. [16] summarized the key themes from the First International Workshop on DePIN 2023, focusing on issues such as scalability, interoperability, and governance.

This study differs from earlier work by providing a broader analysis of DePIN systems that integrates technical models with socio-economic factors. Previous research has often concentrated on specific technical components, project types, or individual case studies. In contrast, this

Table 6
Summary of results of research works from the Scopus database.

Year	Reference	Typology	Type of research	Short description
2023	Sarkar [20]	Conference	Framework Proposal	Introduces the Generalized DePIN (GDP) protocol, a modular framework for decentralized physical infrastructure networks.
2023	Fan and Xu [16]	Conference	Workshop overview	Provides overview of the 1st International Workshop on DePIN including discussions on core concepts and tokenomics.
2023	Ballandies et al. [14]	Conference	Taxonomy	Develops a systematic taxonomy for blockchain-based DePINs encompassing distributed ledger technology and cryptoeconomic design.
2023	Fan and Xu [21]	Conference	Position paper	Outlines a rollup-centric scalable architecture for DePINs using modular design with off-chain computing.
2024	Andrew and Ballandies [13]	Conference	Classification framework	Proposes a decision tree for classifying systems as DePINs based on three-sided markets and token-based supply incentives.
2024	Carreño Aguilera et al. [22]	Journal article	Framework Proposal	Proposes GLOBALPIN, a DAO scheme addressing IoT-DePIN network interoperability and scalability using blockchain and AI.
2024	Ratanpara and Pithadia [23]	Journal article	Literature Review	Provides a comprehensive literature review of DePINs analyzing capabilities versus centralized systems.
2024	Sarkar et al. [24]	Preprint	Platform Architecture	Introduces dTelecom, a DePIN-based architecture for decentralized real-time communication leveraging blockchain.
2024	Olshansky et al. [25]	Preprint	AI Inference	Shows how POKT Network extends its decentralized RPC infrastructure to provide permissionless AI inference services.
2024	Hu and Ting [1]	Conference	Design Fiction	Presents a design fiction manifesto exploring blockchain-nurtured AI agents and Human-AI symbiosis.
2024	Zhou et al. [26]	Conference	Review	Reviews gaps between Web 3.0 and Web 4.0, focusing on native AI entities and decentralized physical infrastructure.
2024	Fan [10]	Conference	Framework Proposal	Presents the modular DePIN infrastructure thesis for building applications from community-owned hardware elements.
2024	Chiu et al. [27]	Conference	Case Study	Introduces CircularX 2.0, a DePIN solution for transforming waste into regenerative resources using blockchain.
2024	Lin et al. [9]	Conference	Survey	Provides comprehensive DePIN exploration, presenting a five-layer architecture and survey of Physical and Digital Resource Networks.
2024	Heiss et al. [6]	Conference	Mechanism Design	Proposes a credential-based device registration mechanism using Zero-Knowledge Proofs to verify device credentials.
2024	Assen et al. [15]	Conference	Performance Analysis	Evaluates DePIN performance for serverless computing compared to traditional cloud providers using Acurast.
2024	Pillai and Bui [12]	Conference	Review	Reviews blockchain Layer 2 solutions and proposes DePINs as data availability layer solutions for modular blockchain systems.
2025	Caprolu et al. [11]	Book Chapter	Security analysis	Analyzes security and privacy implications of DePIN infrastructure across Network Services and AI-based computation.
2025	Milionis et al. [28]	Preprint	Game-Theoretic Analysis	Introduces a formal model for eliciting unverifiable information from self-interested sources in DePIN applications.
2025	Kalabić et al. [29]	Conference	Tokenomics Analysis	Provides game-theoretic analysis of deflationary burn-and-mint tokenomics in DePINs, identifying deflation thresholds.

work takes a wider view, examining the historical evolution, architectural structure, incentive design, and market conditions of DePINs. The result is a unified framework that links the technical foundations of these systems with their economic and operational realities.

3.2. DePIN projects and theoretical proposals

Assen et al. [15] presented a comparative analysis of Acurast, a Decentralized serverless cloud platform, and centralized alternatives such as Google Cloud Platform. Their evaluation considers computational efficiency, energy consumption, node distribution, and deployment success rates. The study also examines token-based incentive mechanisms, highlighting how economic design affects the performance and sustainability of Decentralized infrastructure.

Petr et al. [24] proposed the dTelecom architecture, which uses blockchain to construct a Decentralized and scalable communication network. In a related study, Olshansky et al. [25] expanded the functionality of the POKT Network's Decentralized RPC infrastructure, enabling permissionless inference for large language models (LLMs) and aligning incentives among model developers, hardware providers, and other participants.

Focusing on modular design, Fan et al. [10] introduced a framework in which core components, connectivity, storage, and computation, operate as interoperable modules, adaptable to varied use cases. To address scalability, Fan et al. [21] examined rollup-centric architectures that combine on-chain security with off-chain execution and zero-knowledge proofs (ZKPs), supporting more efficient Decentralized systems.

Heiss et al. [6] addressed security and device onboarding in DePINs by proposing a credential-based registration (CDR) mechanism based on zero-knowledge proofs. This design enables secure and privacy-preserving device enrolment in Decentralized networks.

Chiu et al. [27] presented CircularX, a DePIN initiative focused on regenerative waste management. The project uses a three-layer architecture to support local resource trading, aiming to promote circular economies while remaining scalable for broader deployment.

Milionis et al. [28] developed a formal model for extracting reliable signals from network participants under specific conditions such as source identifiability. Their approach applies to scenarios including location verification and bandwidth measurement, improving the reliability of data contributed by participants.

Finally, Kalabić et al. [29] conducted a game-theoretic analysis of burn-and-mint tokenomics under deflationary conditions. Their findings identify the deflation threshold needed to sustain token value and propose securing contributor rewards in fiat currency to limit the risk of under-incentivization.

3.3. Systemic and conceptual studies

Andrew et al. [13] proposed a decision-tree framework for classifying DePIN systems. Their model is structured around three criteria: the use of blockchain-based token incentives, the formation of triadic platforms connecting infrastructure providers, service operators, and end-users, and the strategic deployment of physical assets as economically significant activities. A key distinction in their framework is between location-independent (DePIN-LI) and location-dependent

(DePIN-LD) infrastructure, which helps distinguish DePINs from both Web 2.0 and other Web 3.0 systems.

Building on this foundation, Caprolu et al. [11] positioned DePINs within a broader user-oriented Web 3.0 model. Their architecture combines blockchain, smart contracts, IoT, tokenisation, and tokenomics, and contrasts Decentralized zero-trust systems with traditional centralized approaches.

Carreño Aguilera et al. [22] examined scalability and interoperability challenges in Decentralized IoT networks. They advocate for the use of Decentralized autonomous organizations (DAOs) as a governance model capable of addressing these systemic issues.

Looking further ahead, Zhou et al. [26] introduced the concept of Native AI Entities (NAEs) within a prospective Web 4.0 framework. These autonomous agents operate within a network that integrates blockchain nodes, AI modules, semantic technologies, and VR/AR interfaces. NAEs follow a full operational cycle from deployment to decommissioning, supported by Decentralized funding and smart contract-based coordination.

4. DePIN architecture and applications

In this section, we examine DePIN systems in detail. We present a six-layer architecture for Decentralized Physical Infrastructure Networks (DePIN) obtained by analyzing the 21 leading DePIN projects across six categories. Although implementations vary by project type and technical constraints, the proposed architecture provides a clear structure for comparing and understanding reward mechanisms across the DePIN ecosystem. We validate its practical application using it to describe well-established examples such as Helium, Render, and Filecoin. Then we examine DePIN systems focusing on application categories, and governance strategies. The discussion considers both general patterns and specific reference to the 21 projects introduced in Section 2.

4.1. Six-layer architecture

Our six-layer architecture follows a structured, multi-phase methodology aimed at ensuring thorough coverage and empirical support. This framework favors a descriptive approach over prescriptive modeling. It acts as an analytical and conceptual tool for understanding current DePIN implementations. Its validity is proven by the framework's ability to categorize all studied projects. The main value of the architecture lies in offering a common structure, enabling consistent comparisons among project layers, identification of common patterns and differences, and understanding architectural trade-offs.

4.1.1. Methodological approach

The methodology involves five phases. The first phase, workflow analysis, begins with a study of definitions of DePIN across different sources and its historical background. It then involves a detailed examination of operational workflows across 21 selected projects. We carefully documented the full life cycle of each project, from service delivery to reward distribution. Sources included official documents, whitepapers, GitHub repositories, blogs, and network explorer data. This analysis showed that, despite varying application fields such as storage, wireless networking, or AI, there was a consistent pattern in operational phases: infrastructure provisioning by distributed operators, service delivery to users, contribution validation, blockchain-based coordination, reward computation, and final token distribution through a user redemption layer.

The second phase, the taxonomy, uses an inductive method to identify common system elements. Building on the workflow analysis, we identified recurring functional components across projects regardless of their technical details. These components are naturally grouped into distinct functional layers addressing specific architectural concerns.

The taxonomy arises from observed similarities across diverse implementations, not imposed by theory. For instance, all projects require mechanisms to verify physical contributions, using different techniques like cryptographic proofs in Filecoin, consensus validation in Bittensor, or hardware attestation in Helium. Despite implementation differences, the core need for verification remains consistent.

In the third phase, architecture mapping, we systematically link projects to architectural components. This process confirms the framework's scope and applicability. We documented each project's integration with taxonomy layers, emphasizing similarities and differences. Findings show all projects fit the six-layer model without special cases or interpretative adjustments. This widespread applicability across storage, compute, wireless, AI, sensor, and bandwidth networks demonstrates that the architecture captures key structural patterns common to DePIN systems.

The fourth phase, implementation analysis, investigates specific design choices within projects. Instead of viewing projects as uniform, we explore how different requirements, constraints, and target users influence decisions. This reveals a wide range of design options at each layer, as projects balance priorities like security versus efficiency, decentralization versus performance, or simplicity versus complexity. Documenting these variations offers valuable insights into the trade-offs future DePIN projects will face.

The final phase, comparative evaluation, assesses architectural maturity and trade-offs. It identifies how different architectural choices affect system performance and user adoption. The evaluation considers factors like decentralization level, attack resilience, scalability, resource use, and readiness for production. This survey features successful patterns and ongoing challenges within the DePIN landscape.

4.1.2. Architecture overview

The six-layer model, illustrated in Fig. 3 serves as a general framework for understanding reward systems in DePIN projects. The *Physical Layer* consists of the hardware or physical resources provided by users across six network categories, such as Compute Networks, Storage Networks, Sensor Networks, Wireless Networks, Bandwidth Networks, and AI Networks. The *Verification Layer* ensures that contributions meet defined requirements through cryptographic proofs, consensus mechanisms, and hardware attestation. The *Oracle & Off-Chain Layer* enables integration of external data and supports off-chain computations when required. The *Blockchain Layer* manages consensus, settlement, and the maintenance of the on-chain state. The *Reward Scaling Layer* determines the calculation and distribution of incentives based on distribution and quality. Finally, the *Redemption Layer* also called application layer concerns the mechanisms by which users receive or redeem, and utilize their tokens through exchanges, staking, and governance participation. These six layers represent the minimum complete set of functional requirements for DePIN systems. Addressing, how participants are coordinated trustlessly, how contributions are incentivized, and how users access rewards.

4.2. Descriptions of the six layers

In this section, we provide a precise description of the six layers of DePIN systems, according to the proposed architecture.

4.2.1. Physical layer

The Physical Infrastructure Layer comprises the hardware resources that deliver services to network users. It includes six main network categories, each fulfilling different infrastructure functions. Compute Networks offer processing power via distributed GPUs, CPUs, and specialized processors. Render Network manages 5600 NVIDIA GPUs for 3D rendering. Akash Network runs 797 active container leases for cloud computing. Golem Network supports general computational tasks, while AIOZ Network has 277,810 content delivery nodes for video streaming. Storage Networks enable data persistence through

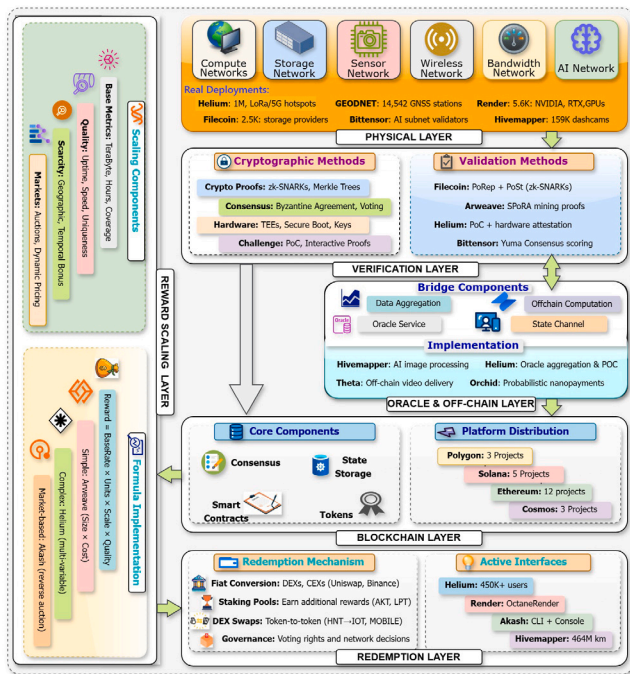


Fig. 3. DePIN User Reward Architecture: This architecture illustrates the complete multi-layer flow from physical contributions and cryptographic verification, through blockchain-based token minting and dynamic reward scaling, to user redemption mechanisms such as staking, swaps, and governance.

distributed storage systems, with Filecoin managing over 2500 storage providers handling petabytes of data. Arweave offers permanent data storage with its permaweb architecture, and Storj provides decentralized, S3-compatible storage. BitTorrent Chain employs the BTFS protocol for distributed file sharing.

Sensor Networks gather data via IoT devices and hardware, with Hivemapper deploying 159,000 dashcams that mapped 464 million km of roads. DIMO connects 173,000 vehicles for telematics, while GEODNET uses 14,542 GNSS base stations across 142 countries for positioning data. OriginTrail tracks supply chain data through distributed nodes. Wireless Networks provide connectivity through community-operated infrastructure, such as Helium’s 1 million LoRaWAN and 5G hotspots globally, WiFi Map’s crowd-sourced access points, and bandwidth networks enhancing content delivery and privacy. Theta Network manages edge caching nodes for video streaming, Live-peer operates about 100 transcoding orchestrators, and Orchid oversees VPN bandwidth providers for privacy. AI Networks enable machine learning and AI services, with Bittensor coordinating GPU and TPU miners, Fetch.ai running autonomous AI agents, Aethir offering enterprise GPU infrastructure, and Node AI facilitating GPU marketplace lending. This layer supplies raw data like sensor readings, storage proofs, computational outputs, and connectivity metrics, all of which require verification before rewards are distributed.

4.2.2. Verification layer

The Verification Layer verifies contributions from the Physical Layer using cryptographic methods like Proof-of-Coverage for wireless networks, Proof-of-Replication for storage, and Proof-of-Render for computation. These methods ensure contributions meet reliability and quality standards before they qualify for rewards. Validation occurs on-chain via smart contracts, Filecoin uses zk-SNARKs for Proof-of-Replication and Proof-of-Spacetime to confirm storage providers hold the data without revealing content. Arweave employs Succinct Proof of Random Access for storage verification, and Helium uses witness signatures along

with hardware attestation through embedded cryptographic keys to prevent GPS spoofing and virtual hotspot fraud. Off-chain verification handles tasks involving extensive computation or subjective judgment. Hivemapper filters low-quality images with AI before submitting hashes to Solana, while Bittensor uses Yuma Consensus for validators to agree on machine learning outputs based on stake weight. The Render is validated via OctaneBench GPU scores. This layer collaborates with the Oracle Layer when additional processing is needed.

4.2.3. Oracle and off-chain data layer

This layer handles data that cannot be directly verified on-chain, aggregating and validating off-chain contributions before transmitting them to the blockchain. It enables system scalability while preserving data integrity.

Post-Solana migration, Helium uses off-chain validators to assess Proof-of-Coverage by gathering witness reports before enabling lazy claims, reducing on-chain transactions by over 1,000x. Hivemapper uses centralized AI for image evaluation and map-tile generation before submitting contribution hashes. Theta delivers video content off-chain while settling micropayments periodically, enabling thousands of microtransactions per second. Orchid routes VPN traffic through probabilistic nanopayment channels, where expected value matches bandwidth without per-packet settlement.

These design patterns reflect both the bottlenecks of centralization and the necessity of scalability. Notably, Filecoin, Arweave, Akash, Render, and Golem minimize oracle dependence through on-chain cryptographic verification.

4.2.4. Blockchain layer

The Blockchain Layer provides the execution environment in which smart contracts process validated contributions and manage token issuance, ensuring that only authenticated inputs trigger rewards. Platform distribution shows that Ethereum hosts 12 projects, Solana supports 5, Cosmos SDK underlies 3, and Polygon hosts 3. Storage networks vary: Filecoin operates a custom Expected Consensus mechanism, Arweave runs Proof-of-Access, Storj uses hybrid coordination, and BitTorrent utilizes TRON DPoS. Compute networks predominantly use established platforms: Render migrated to Solana, Akash uses Cosmos SDK, Golem operates on Ethereum with a Polygon sidechain, and AIOZ deploys on Cosmos SDK and BSC.

Wireless networks illustrate an evolution: Helium migrated to Solana (from 2 TPS to 4000), and WiFi Map uses Polygon. AI networks employ varied platforms: Bittensor runs a Substrate-based custom chain, Fetch.ai uses Cosmos SDK, Aethir deploys on Arbitrum and Solana, and Node AI operates on Ethereum. Sensor networks favor established chains: Hivemapper on Solana, DIMO on Polygon and Base, GEODNET on Polygon, and OriginTrail is multi-chain.

Bandwidth networks include Theta’s custom multi-BFT chain, Livepeer on Ethereum and Arbitrum, and Orchid on Ethereum. Filecoin employs StorageMinerActor contracts, minting FIL tokens for verified storage. Helium uses a Burn-and-Mint Equilibrium model, where HNT burns generate specialized tokens (IOT, MOBILE), maintaining economic balance.

4.2.5. Reward scaling layer

The Reward Scaling Layer governs reward distribution based on verified contributions, network conditions, and economic parameters. While implementation details differ across projects, most DePIN systems follow a structured approach that includes a base reward rate, the quantity of resources contributed, and a scaling factor that adjusts incentives according to demand and participation. Most systems follow a the given general structure.

$$\text{Rewards} = \text{BaseRate} \times \text{ResourceUnits} \times \text{ScalingFactor} \times Q$$

In Filecoin’s storage network, rewards are determined using the Storage Power Consensus mechanism, which accounts for multiple

Table 7
How users earn crypto with DePIN.

Project	Token	Description	Category	Source
Render Network	RENDER	Node operators provide GPU power for 3D rendering and AI workloads	Resource Contribution	RenderNetwork
Akash Network	AKT	Providers lease computing resources through decentralized marketplace	Resource Contribution	AkashNetwork
AIOZ Network	AIOZ	Node operators contribute computing, storage, and bandwidth for CDN	Hybrid	AIOZNetwork
Golem Network	GLM	Providers rent unused computing power with pay-per-use compensation	Resource Contribution	GolemNetwork
Fetch.ai	FET	Users earn through staking and creating autonomous AI agents	Network Participation	Fetch.ai
Aethir	ATH	Enterprise GPU providers earn through Proof of Rendering Work	Resource Contribution	Aethir
Bittensor	TAO	Miners produce AI models; validators use Yuma Consensus	Hybrid	BittensorDocs
Filecoin	FIL	Storage providers earn through block rewards and storage fees	Resource Contribution	FilecoinDocs
BitTorrent	BTT	Users earn through seeding torrents and running BTFS nodes	Hybrid	BTFS
Arweave	AR	Miners permanently store data using Proof of Access consensus	Resource Contribution	ArweaveDocs
Storj	STORJ	Storage Node Operators earn monthly payments for capacity sharing	Resource Contribution	StorjDocs
Helium	HNT	Hotspot operators provide wireless coverage for IoT devices	Resource Contribution	HeliumDocs
WiFi Map	WIFI	Users earn through airdrops for contributing WiFi hotspots	Data Monetization	WiFiMap
Theta Network	THETA/TFUEL	Edge Node operators contribute bandwidth for video transcoding	Resource Contribution	ThetaDocs
Livepeer	LPT	Users earn through delegation to Orchestrators for transcoding	Network Participation	LivepeerDocs
Orchid	OXT	VPN node operators stake tokens and provide bandwidth services	Hybrid	OrchidDocs
Hivemapper	HONEY	Users drive with dashcams for street imagery collection	Hybrid	HivemapperDocs
DIMO	DIMO	Vehicle owners earn by connecting cars and streaming data	Data Monetization	DIMODocs
OriginTrail	TRAC	Users run DKG Core Nodes and participate in delegated staking	Network Participation	OriginTrailDocs
GEODNET	GEOD	Users deploy GNSS base stations for GPS correction data	Resource Contribution	GEODNETConsole
Node AI	GPU	Users lend GPU hardware for AI processing and staking	Hybrid	NodeAI

factors to incentivize reliable, long-term participation. The reward calculation considers the amount of storage capacity provided (Resource Units), the duration of the storage commitment (Scaling Factor), and the quality of service delivered (Q, the quality factor). FIL tokens are issued proportionally based on these parameters, creating economic incentives that promote sustained service provision and network reliability.

Helium applies a similar approach under the HIP-20 protocol. Hotspot operators earn IOT or MOBILE tokens based on the density of their network coverage (Resource Units) and the amount of data transmitted (Scaling Factor). This model rewards participants who provide useful infrastructure while dynamically adjusting incentives to reflect evolving usage patterns.

Hivemapper uses AI-based quality control to filter out low-resolution, duplicate, or irrelevant geospatial images, ensuring that only meaningful data is rewarded. Filecoin applies slashing penalties to storage providers that fail to meet uptime standards. In Decentralized computing networks, GPU rewards are often calculated dynamically based on demand, rather than through fixed rates, enhancing resource efficiency. This layer interacts with the Verification and Token Distribution Layers, enabling real-time adjustments to maintain system effectiveness.

Table 7 summarizes how users earn cryptocurrency in the 21 leading DePIN projects selected in Section 2. Participants contribute physical or digital resources, such as bandwidth, storage, or compute power, in return for token-based rewards. The table integrates findings from Binance Research [30], the Messari DePIN Report [19], and the Cryptomeria Report [31]. It illustrates the scale of the ecosystem, with millions of active devices and a combined market capitalization of \$50 billion. Despite more than \$1.2 billion in cumulative investments and rapid network expansion, unresolved issues remain, including uncertainty around long-term revenue models and the high initial cost of hardware.

4.2.6. User redemption layer

The Redemption Layer allows contributors to convert their earned tokens into practical assets and take part in governance, offering access to liquid markets and options for reinvestment.

Redemption options include converting to fiat via DEXs like Uniswap and CEXs like Binance, staking pools that provide extra rewards such as AKT and LPT, token swaps between network-specific tokens like HNT and IOT/MOBILE, and governance participation with voting rights. Helium users exchange tokens using Jupiter DEX on Solana. Filecoin

providers stake FIL to enhance storage reliability. Hivemapper contributors trade HONEY tokens on various exchanges. Different interfaces show varying levels of activity: Helium serves 450,000 users with mobile wallet apps; Render integrates with OctaneRender plugins for Cinema 4D and Blender; Akash offers CLI and web console supporting 797 leases; and Hivemapper runs gamified applications with 464 million kilometers of mapped data.

4.3. Architecture validation

To validate the architecture, we evaluated its applicability using the 21 projects introduced in Section 2 as a benchmark.

4.3.1. Coverage analysis

To validate the architecture, we evaluated its applicability to the 21 projects introduced in Section 2. Using the available documentation, we examined the presence and the specific implementation of the six identified layers across all projects. Table 8 presents the resulting comprehensive mapping.

Quantitative coverage analysis reveals full implementation across all layers. Layer 1 (Physical Infrastructure) shows 21 of 21 projects (100%) with explicit implementations spanning all six network categories. Layer 2 (Verification and Validation) also shows (100%) with explicit implementations employing diverse verification techniques. Layer 3 (Oracle and Off-Chain) shows 16 of 21 projects (76%) with explicit implementations and 5 projects (24%) with minimal oracle use. Notably, Filecoin, Arweave, Akash, Render, and Golem reduce oracle dependence by relying primarily on on-chain cryptographic verification. Layer 4 (Blockchain Coordination) demonstrates (100%) projects using blockchain infrastructure. Layer 5 (Reward Scaling) shows projects (100%) with explicit implementations. Layer 6 (Redemption) similarly demonstrates 21 of 21 projects (100%) with explicit implementations.

The identified inter-layer dependencies, derived through detailed analysis, reveal how architectural choices cascade through the system. The type of infrastructure determines the feasible verification approaches, with storage networks employing cryptographic proofs, whereas wireless networks require Proof-of-Coverage augmented by oracles. Verification complexity drives oracle requirements: projects using heavy cryptographic proofs exhibit lower oracle dependence, while those verifying physical presence require more extensive off-chain aggregation. Oracle architecture influences blockchain throughput requirements, with lazy-claim mechanisms enabling migration to high-throughput chains. Blockchain capabilities constrain both the frequency

Table 8
Mapping of 21 DePIN Projects to Six-Layer Architecture.

Project	Physical layer	Verification layer	Reward protocol	Oracle & Off-Chain layer	Blockchain layer	Reward scaling	Redemption layer
Helium	✓	✓	Proof-of-Coverage	✓	Helium/Solana	✓	✓
Filecoin	✓	✓	Proof-of-Spacetime/PoRep	×	Filecoin	✓	✓
Render	✓	✓	Proof-of-Render	×	Ethereum/Solana	✓	✓
Akash	✓	✓	Tendermint BFT	×	Cosmos SDK	✓	✓
Livepeer	✓	✓	Delegated PoS	✓	Ethereum/Arbitrum	✓	✓
Hivemapper	✓	✓	AI-powered Validation	✓	Solana	✓	✓
DIMO	✓	✓	W3C Standard IDs	✓	Polygon/Base	✓	✓
OriginTrail	✓	✓	Multi-chain Consensus	✓	Ethereum/Gnosis	✓	✓
Bittensor	✓	✓	Yuma Consensus	✓	Substrate-based	✓	✓
Theta	✓	✓	Multi-level BFT	✓	Theta	✓	✓
GEODNET	✓	✓	Proof of Accuracy/PoS	✓	GEODNET Chain	✓	✓
Fetch.ai	✓	✓	Tendermint PoS	✓	Cosmos SDK	✓	✓
Aethir	✓	✓	Checker Nodes (2N+1)	✓	Ethereum/Arbitrum	✓	✓
Golem	✓	✓	Verification by Redundancy	×	Ethereum/Polygon	✓	✓
Arweave	✓	✓	SPoRA	✓	Arweave	✓	✓
Storj	✓	✓	Satellite Audits	✓	Ethereum	✓	✓
WiFi Map	✓	✓	Community Verification	✓	Polygon	✓	✓
Orchid	✓	✓	Stake-weighted Randomization	✓	Ethereum	✓	✓
BitTorrent	✓	✓	Proof of Storage	✓	TRON/BitTorrent Chain	✓	✓
AIOZ	✓	✓	Tendermint dBFT	✓	AIOZ Chain/BSC	✓	✓
Node AI	✓	✓	Computational Proof	✓	Ethereum	✓	✓

and complexity of reward calculations, with high-cost chains necessitating simpler reward formulas, whereas low-cost chains support sophisticated multivariable calculations. Reward transparency shapes application design, as simpler reward formulas enable more straightforward user interfaces.

All 21 projects align cleanly with all six layers without exception, confirming the universal applicability of the framework. No pushed variations were required; Projects naturally fit the framework without artificial decomposition, special case handling, or other forced interpretations. The architecture accommodates both simple implementations, such as Arweave’s straightforward permanent storage model with minimal oracle dependence, and complex multi-layer designs, such as Helium’s sophisticated validation, which combines Proof-of-Coverage, hardware attestation, oracle aggregation, and geographic incentive engineering. This universal applicability across storage, compute, wireless, AI, sensor, and bandwidth networks provides strong evidence that the architecture captures fundamental structural patterns common to DePIN systems in production deployments.

Table 8 shows that each project employs a distinct blockchain layer. The choice of blockchain influences the overall performance of the DePIN project and the associated transaction costs.

4.3.2. Architectural flexibility and limitations

The six-layer model captures the essential functional components of DePIN systems, but implementations vary significantly among projects. Some projects combine layers shown in Fig. 3, while others implement them with different emphases based on technical requirements. Layer combination occurs in several cases. Golem and Arweave merge verification with on-chain consensus, embedding proof validation directly into blockchain protocols. Filecoin and Render use strong cryptographic proofs that eliminate the need for distinct oracle layers. Conversely, Hivemapper and DIMO rely heavily on external oracles to validate geographic location and quality metrics that cannot be verified cryptographically.

Architectural evolution shows that layer implementations change over time. Helium’s migration to Solana shifted the project from minimal oracle dependence to heavier reliance on off-chain aggregation, reducing on-chain transactions by over 1000x while maintaining security through oracle signatures. Layer prominence also varies by domain. Storage networks emphasize cryptographic verification with minimal oracle usage. Wireless networks require substantial oracle infrastructure for physical-world data aggregation. Compute networks minimize

oracles for deterministic tasks, while AI networks employ consensus-based validation for non-deterministic outputs. The Blockchain Coordination Layer exhibits distinct trade-offs. Five projects operate custom blockchains (Filecoin, Arweave, Theta, Bittensor, BitTorrent), while most others leverage established platforms to reduce development costs. We assessed blockchain choices using five key metrics: maximum transactions per second (Max TPS), average transactions per second (Avg TPS), consensus mechanism, and average transaction cost in USD (as of June 2025). Table 9 presents these assessments. Average transaction fees in native tokens were computed using 24-hour rolling averages from official blockchain explorers (Solana FM, Etherscan, Polygonscan), then converted to USD using real-time token prices from CoinGecko and CoinMarketCap.

The Reward Scaling Layer shows wide variation in complexity, ranging from Arweave’s simple data-size-based calculation to Helium’s multivariable geographic system, reflecting different approaches to incentive alignment and transparency.

Despite these variations, the six-layer framework successfully categorizes all surveyed projects without requiring special cases or modifications, indicating that these layers represent fundamental architectural requirements for token-incentivized physical infrastructure networks.

4.4. DePIN categories of application

DePIN encloses a broad range of blockchain projects that utilize distributed physical resources to deliver real-world services. These networks incentivize participants to contribute hardware, data, or computational capacity in exchange for token-based rewards, providing an alternative to centralized infrastructure. Decentralized Physical Infrastructure Networks (DePINs) are typically grouped into two primary categories based on the types of resources they coordinate: Physical Resource Networks (PRNs), which manage location-dependent and non-fungible assets, and Digital Resource Networks (DRNs), which oversee fungible and location-agnostic resources [9,10,21,32]. Table 10 summarizes the various categories of DePIN projects according to their principal application domains, highlighting the sectors being reshaped by Decentralized infrastructure.

Classifying DePIN projects helps to clarify both their application scope and the types of infrastructure they support. Table 10 summarizes the categories used in recent analyses by Binance [30], Messari [19,33], and Cryptomeria [31]. The categories *Compute*, *Wireless*, and *Sensors* are widely recognized due to their close association with physical infrastructure. Other categories, such as *Energy*, *Identity*, *Logistics*, *Mapping*,

Table 9
DePIN Blockchain layer Specifications.

Blockchain	DePIN projects	Max TPS	Avg. TPS	Consensus	Avg. Tx cost	Official sources
Solana	Helium, Render, Hivemapper, Aethir	65,000	1330–4000	PoH + PoS	\$0.00025–0.0025	SolanaDocs
Polygon PoS	DIMO, WiFi Map, GEODNET	714	34–39	Dual-layer PoS	\$0.001	PolygonDocs
Ethereum	Storj, Orchid	119	15–25	PoS	\$0.02–0.19	EthereumDocs
TRON	BitTorrent	2000	127–141	DPoS	\$0.00–0.0065	TRONDocs
Arbitrum One	Livepeer	40,000	20–29	Optimistic Rollup	\$0.007–0.015	ArbitrumDocs
Cosmos SDK	Akash, AIOZ, Fetch.ai	3200–10,000	Varies	Tendermint BFT	\$0–0.0089	CosmosDocs
Filecoin	Filecoin	30	2	Expected Consensus	\$0.01–0.03	FilecoinDocs
Arweave	Arweave	50,000	450–500	Proof of Access	\$0.0075	ArweaveDocs
Theta	Theta	1,000+	N/A	Multi-level BFT	\$0.000065–0.037	ThetaDocs
Substrate	Bittensor	N/A	N/A	Yuma Consensus	Variable	BittensorDocs

Table 10
Unified DePIN Categories Table.

Category	Sources	Definition	Relevant Projects
Sensors network	Messari, Binance, Cryptomeria	IoT-based data collection from devices such as dashcams and weather stations.	Hivemapper, DIMO, GEODNET, NATIX, WeatherXM
Compute network	Messari, Binance, Cryptomeria	Distributed computing for AI, rendering, and general tasks.	Akash, Render, Nosana, Aethir, Gensyn, io.net
Wireless network	Messari, Binance, Cryptomeria	Decentralized networks for internet access, 5G, and IoT.	Helium, DAWN, WiFi Map, Okic, Pollen Mobile, Althea, Wayru, Foam
Storage network	Binance, Cryptomeria	Decentralized data storage services.	Filecoin, Arweave, Storj, Sia, BNB Greenfield
Energy network	Messari, Cryptomeria	Decentralized energy systems, including peer-to-peer sharing and renewables.	Daylight, Glow, DeCharge, Project Zero, PowerPod, Inferix, GEODNET
AI/ML network	Binance, Cryptomeria	Decentralized AI infrastructure for training, inference, and computation.	Bittensor, Ritual, Nosana, Gensyn, Virtuals Protocol
Bandwidth	Binance	Shared network capacity for data transmission and internet access.	Orchid, Theta Network, Livepeer
Identity network	Messari	Decentralized identity verification and authentication.	Worldcoin, Anymal, Braintrust
Logistics network	Messari	On-chain coordination of goods and services.	Dtravel, Nosh, 3DOS, HEALE
Mapping/Navigation	Cryptomeria	Crowdsourced mapping and navigation data.	Hivemapper, Foam, NATIX
DePIN & ZK	Cryptomeria	Use of Zero-Knowledge proofs for privacy, scalability, and computation validation.	Zorp, Nosana, Filecoin (ZK proofs), Gensyn (ZK for AI)

and ZK, are more appropriately understood as application domains. Accordingly, projects in these domains are reassigned to one of the core categories detailed below.

4.4.1. Physical Resource Networks (PRNs)

Physical Resource Networks manage location-dependent and non-fungible assets [9,10,21] and are classified into subcategories such as sensor networks and wireless networks.

Sensor networks. Sensor Networks, a subset of Physical Resource Networks (PRNs), are responsible for securely capturing and monitoring real-world data streams collected by Internet of Things (IoT) devices. They typically provide non-fungible services tied to specific geographic locations [9,10,21]. These networks facilitate data collection for diverse applications, including mobility, location services, mapping, and environmental monitoring [9,10,21]. Projects such as DIMO, Hivemapper, GEODNET, and OriginTrail enhance data accuracy through cryptography, planning tools, and environmental monitoring frameworks [9,10].

Wireless networks. Wireless Networks, also known as Decentralized Wireless (DeWi), incentivize individuals to deploy wireless networking hardware to provide connectivity services such as 5G, WiFi, LoRaWAN, and Bluetooth [9,34]. As PRNs, they offer non-fungible, location-dependent connectivity [9,21]. Prominent examples include Helium and WiFi Map [9,10,34].

4.4.2. Digital resource networks (DRNs)

Digital Resource Networks coordinate fungible assets, indicating that the value of the resource is independent of its physical location [10,21].

Compute networks. Compute Networks are a class of Digital Resource Networks (DRNs) that aggregate distributed and often underutilized computational resources, including CPUs, GPUs, and FPGAs to provide scalable, fungible processing power [9,10,21,35]. By pooling these resources, they deliver scalable and cost-effective computing services. These networks function as marketplaces for resource consumption, supporting applications in rendering, machine learning, high-performance computing, real-time rendering, gaming, and complex Artificial Intelligence (AI) training and inference workloads [35]. Notable examples include Render Network, Akash Network, Golem, AIOZ Network, and Aethir, which collectively reduce dependence on traditional cloud providers [9,10,32,35].

AI networks. AI Networks specialize in providing Decentralized resources for the Artificial Intelligence industry by aggregating compute and data [9]. They support Decentralized AI development by distributing model training, inference, and dataset access. Participants are rewarded with tokens for contributing computational resources or data, thereby enabling collaborative model development and greater transparency. These networks facilitate critical services such as AI model training, inferencing, and the operation of GPU marketplaces [9,

35]. Key projects include Bittensor, which focuses on AI agent platforms; Fetch.ai; Aethir, which aggregates enterprise-grade GPU resources globally to support computationally intensive workloads; and Node AI [9,35].

Storage networks. Storage Networks provide Decentralized data and file retention services, classifying them as Digital Resource Networks [9, 21]. They replace centralized cloud storage with Decentralized systems secured by cryptographic proofs. Unlike centralized cloud providers, these systems encrypt and distribute data across peer-to-peer nodes, relying on cryptographic mechanisms such as Proof-of-Replication (PoRep) and Proof-of-Spacetime (PoSt) to guarantee data persistence and integrity [32,36]. Projects such as Filecoin, Arweave, BitTorrent, and Storj offer encrypted, distributed, and censorship-resistant data storage for users and organizations [9,10,36].

Bandwidth networks. Bandwidth Networks are Digital Resource Networks designed to monetize unused network capacity, typically for services requiring efficient content distribution [9]. These networks leverage unused network capacity for services such as streaming, Decentralized VPNs, and peer-to-peer content delivery. These services include the development of Decentralized Virtual Private Networks (VPNs) and Content Delivery Networks (CDNs) [9]. Projects like Theta Network, Orchid, Mysterium, and Livepeer use token-based rewards to encourage bandwidth sharing and improve distribution, while Meson focuses on content delivery [9].

4.5. Governance of DePIN projects

Governance in DePIN projects refers to the mechanisms by which decisions are made about infrastructure deployment, reward systems, and community involvement.

Governance structures vary widely in terms of decentralization, authority distribution, and stakeholder participation. Primary stakeholders typically have the most immediate influence over decisions and operations. We identify three main governance types: DAO-based, foundation led, and hybrid models.

Table 11 provides a classification of the selected DePIN projects by governance model. It identifies the model used (DAO, foundation-led, or hybrid), the main decision-making bodies, and the formal documents or processes that define these structures. This classification supports comparison across projects and contributes to understanding how governance design shapes infrastructure and network development.

4.5.1. DAO-based governance

DAO-based governance reflects the most Decentralized coordination model, where decisions are made entirely on-chain and implemented through token-weighted voting. These systems often encourage long-term engagement through mechanisms such as voting escrow or token lockups, which increase voting power based on commitment duration.

For example, the *Helium network* (Governance, HIP) employs a veto model. Participants can lock tokens for up to four years to gain enhanced voting rights. Proposals, called Helium Improvement Proposals (HIPs), are submitted to community voting for approval.

Likewise, the *Akash Network* [37] follows a one-token, one-vote approach, allowing any token holder to vote directly on decisions. Important changes, such as the acquisition of Praetor to improve compute provider onboarding, were approved through binding on-chain votes.

4.5.2. Foundation-led governance

In foundation-led governance, authority rests largely with a central organization. Community input may be collected through forums or discussion platforms, but such feedback typically does not carry formal voting weight. Final decisions are made by the foundation or development team.

For instance, *Filecoin* is governed by the Filecoin Foundation. While miners and contributors can propose improvements through Filecoin

Improvement Proposals (FIPs), the foundation retains ultimate control over whether proposals are accepted or implemented.

ThetaNetwork also operates under a centralized governance model. Theta Labs appoints Guardian Nodes and holds final authority over protocol updates. Although TFUEL delegators may participate in advisory roles, they do not possess independent voting power.

4.5.3. Hybrid governance

Hybrid governance combines structured oversight by a central team with mechanisms for community ratification. Typically, proposals are initiated by a foundation or core developers, while token holders vote to approve or reject them using tools such as Snapshot.

For example, *Livepeer* uses a shared authority system. The development team appoints a working group (GovWork) to manage treasury allocation and project direction, but protocol upgrades require approval through Snapshot voting by LPT holders.

Similarly, *RenderNetwork* relies on the Render Foundation to draft proposals. These are submitted to RNDR stakers, who vote through platforms such as Snapshot or Nation. This arrangement provides a balance between structured planning and community approval.

5. Analysis of depin projects

5.1. Selection process

Twenty-one DePIN projects were selected based on operational status, economic relevance, and category representation. The initial pool was drawn from actively maintained networks with verifiable on-chain activity and available performance metrics. Priority was given to projects with sustained user engagement and measurable infrastructure contributions.

Each project data cross-verified using sources such as official blockchain explorers, DePIN Scan, CoinMarketCap, DePIN Ninja, and Coin-Gecko. To ensure consistency, only projects with a market capitalization of at least five million USD were retained.

The final list spans six categories Compute, AI, Storage, Wireless, Bandwidth, and Sensor and includes projects with both technical and market presence. These are detailed in Table 12.

5.2. DePIN projects

Table 13 presents open-source contribution data for selected DePIN projects, focusing on transparency, community involvement, and development activity. The data was collected using the GitHub API to extract key metrics, including repository URLs, open-source status, contributor counts, GitHub stars, and project creation dates. Each project's main repository was identified and queried programmatically to ensure consistency and accuracy.

Contributor counts reflect developer participation, GitHub stars serve as a proxy for community interest, and creation dates indicate project longevity. The public status of each repository was verified to confirm whether it met open-source criteria. Projects such as Filecoin, BitTorrent, and Livepeer show high levels of community and developer engagement, while others like Aethir and Hivemapper exhibit more limited participation.

Among the 21 projects analyzed, 13 are open source, reflecting a strong emphasis on transparent and collaborative development. These projects collectively account for 24,462 contributors, averaging approximately 1223 contributors per project. Livepeer leads with 3738 contributors, the highest in the group. In total, these repositories have received 45,836 GitHub stars, with an average of 2292 stars per project. Filecoin is the most starred, with 12,584.

A comparison of project creation dates and token launch timelines Table 12 shows varied development strategies. Most projects, such as Golem (created November 1, 2016; token launched November 18, 2016) and Storj (created January 3, 2014; token launched March 19,

Table 11
Governance Taxonomy and Stakeholder Roles.

Project	Type	Token mechanism	Primary stakeholders	Official sources
Helium	DAO-Based	veHNT/veIOT/veMOBILE locks	Hotspot operators, subDAO participants	HeliumDocs , GitHub
Akash	DAO-Based	1 AKT = 1 vote	Compute providers, AKT holders	Messari , Akash
Bittensor	Hybrid	TAO-alpha-token issuance	AI validators, subnet creators	DynamicTAOGuide
Filecoin	Foundation-Led	FIL (non-voting)	Protocol Labs, storage miners	FIPProcess
Theta	Foundation-Led	THETA staking	Enterprise validators, TFUEL delegators	Theta
Livepeer	Hybrid	LPT delegation	Orchestrators, delegators	Livepeer
Render	Hybrid	RNDR staking	GPU providers, Render Foundation	RNPSystem
GEODNET	DAO-Based	veNFT binding	RTK station operators, GEOD holders	GEODNETDocs
DIMO	DAO-Based	DIMO-weighted voting	Vehicle owners, data consumers	DIMOGovernance
Hivemapper	Foundation-Led	HONEY reputation scoring	Map contributors, Hivemapper Foundation	HivemapperMIPs
Fetch.ai	Foundation-Led	FET staking	Agent developers, Foundation	Fetch.aiGovernance
Aethir	Hybrid	ATH staking	Compute providers, enterprises	AethirBylaws
Golem	Foundation-Led	GLM token	Compute providers, Golem Foundation	GolemGovernance
Arweave	DAO-Based	AR mining rewards	Miners, data users	ArweaveLightpaper
Storj	Foundation-Led	STORJ	Storage node operators, Storj Labs	StorjBlog
WiFi Map	DAO-Based	WiFi governance voting	Hotspot owners, WiFi token holders	WiFiMap
Orchid	Hybrid	OXT nanopayments	Bandwidth providers, end-users	OrchidGovernance
BitTorrent	Foundation-Led	BTT utility	TRON Foundation, file sharers	BTTOverview
AIOZ Network	Hybrid	AIOZ staking	CDN node operators, AIOZ team	AIOZValidator
OriginTrail	Hybrid	TRAC staking	Knowledge nodes, Trace Labs	OriginTrailWhitepaper
Node AI	Foundation-Led	GPU proof tokens	AI service providers, Node AI team	NodeAI

Table 12
Selected DePIN projects with market data and reward tokens.

Category	Project	Market cap	Circulating supply	Token	Launch date
Compute	Render	\$1.73B	411.46M	RNDR	2020-06-24
	Akash Network	\$440.13M	247.44M	AKT	2020-10-15
	AIOZ Network	\$321.17M	1.15B	AIOZ	2016-11-18
	Golem	\$286.78M	1.00B	GLM	2016-11-18
AI	Bittensor	\$3.08B	8.38M	TAO	2021-06-15
	Fetch.ai	\$1.85B	2.60B	FET	2019-02-25
	Aethir	\$232.82M	6.70B	ATH	2023-12-15
	Node AI	\$51.75M	97.15M	GPU	2022-07-30
Storage	Filecoin	\$2.04B	633.64M	FIL	2020-10-15
	BitTorrent	\$847.75M	986.06T	BTT	2019-07-08
	Arweave	\$587.17M	65.45M	AR	2018-06-08
	Storj	\$53.27M	143.79M	STORJ	2017-03-19
Wireless	Helium	\$610.27M	177.39M	HNT/IOT	2019-07-29
	WiFi Map	\$8.57M	578.44M	WiFi	2022-11-10
Bandwidth	Theta Network	\$1.25B	1.00B	THETA/TFUEL	2019-03-15
	Livepeer	\$270.15M	38.19M	LPT	2018-05-01
	Orchid	\$54.78M	591.54M	OXT	2019-12-16
Sensor	OriginTrail	\$229.82M	500.00M	TRAC	2017-11-23
	HiveMapper	\$162.99M	4.07B	HONEY	2022-11-14
	GEODNET	\$59.26M	198.17M	GEOD	2021-09-22
	DIMO	\$25.89M	304.35M	DIMO	2022-01-18

2017), were established before their tokens were issued. In contrast, projects like Render Network, Akash Network, and Aethir launched tokens prior to releasing their codebases, suggesting differing priorities between market positioning and open development.

Market data also highlights substantial variation in capitalization and token supply. Bittensor, for example, has a market capitalization of \$3.08 billion with only 8.38 million tokens in circulation, pointing to the influence of token scarcity on perceived value. BitTorrent, by contrast, has an extremely high supply of 986.06 trillion tokens and a market cap of \$847.75 million, reflecting a different tokenomic structure. Render Network and Filecoin illustrate further variation, with market capitalizations of \$1.73 billion and \$2.04 billion, and circulating supplies of 411.46 million and 633.64 million tokens, respectively. These figures reflect a wide range of approaches to valuation, supply dynamics, and strategic growth within the DePIN sector.

Table 14 summarizes the number of active contributors and network sizes for leading DePIN projects, offering a view into their operational scale and user participation. Data was sourced from platforms including Helium Explorer, Hivemapper Explorer, Filscan, Filfox Explorer, the Akash Network Dashboard, and the official WiFi Map portal. Metrics

such as contributor counts, mapped kilometres, available storage, and compute capacity were collected and cross-verified to ensure accuracy and consistency across sources.

5.3. Blockchain activity

For each of the 21 selected projects, blockchain usage was analyzed by identifying the networks they operate on, key contract addresses, and associated transaction volumes. Most projects rely on multiple blockchains rather than a single network, reflecting diverse operational requirement.

Table 15 summarizes the blockchain infrastructures used across the selected projects. While general-purpose blockchains remain dominant, Ethereum is used by 12 projects, Solana by 5, and Binance Smart Chain (BSC) by 4; many also make use of sidechains and specialized networks. These include Polygon and Arbitrum (Ethereum sidechains), as well as Osmosis and Archway (part of the Cosmos ecosystem). Several projects also operate on purpose-built chains: Arweave (for Decentralized permanent storage), Theta Network (for video streaming), Harmony (for cross-chain operations), Energi (with integrated

Table 13
DePIN Projects with open source contributions.

Project	Repository link	Open source	Contributors	GitHub stars	Created date
Render Network	https://github.com/rendernetwork/RNPs	No	3	40	2023-06-15
Akash Network	https://github.com/akash-network/community	Yes	1403	2892	2022-12-14
Golem	https://github.com/golemfactory	Yes	2307	4476	2016-11-01
AIOZ Network	https://github.com/aioz-ai	Yes	11	410	2019-07-24
Bittensor	https://github.com/opentensor/bittensor	No	649	1514	2020-02-14
Fetch.ai	https://github.com/fetchai/docs	Yes	1298	2306	2018-07-06
Aethir	https://github.com/AethirCloud/checker-client	No	35	5	2024-03-26
Node AI	https://github.com/node-real	No	3344	353	2021-09-08
Filecoin	https://github.com/filecoin-project	Yes	2394	12,584	2016-09-05
Arweave	https://github.com/ArweaveTeam	Yes	266	2496	2017-09-14
Storj	https://github.com/storj	Yes	863	5519	2014-01-03
BitTorrent	https://github.com/bittorrent/go-btfs	Yes	2696	3484	2009-10-20
Helium	https://github.com/helium	Yes	2520	5094	2014-02-10
WiFi Map	https://github.com/wifi-map	No	NA	NA	NA
Theta Network	https://github.com/thetatoken	Yes	305	1016	2017-10-18
Orchid	https://github.com/OrchidTechnologies/orchid	Yes	17	683	2019-12-06
Livepeer	https://github.com/livepeer	Yes	3738	2291	2017-01-25
DIMO	https://github.com/DIMO-Network	Yes	1174	102	2020-04-12
HiveMapper	https://github.com/hivemapper	No	468	41	2014-11-14
OriginTrail	https://github.com/origintrail	No	967	521	2017-11-23
GEODNET	https://github.com/geodnet	No	4	9	2021-09-22

Table 14
Contributor & devices involved in DePIN projects.

Project	Active Contributors	Devices & Network Size details	Official Sources
Helium	450,000+ hotspots	1M+ hotspots (990k LoRaWAN, 15k 5G)	HeliumExplorer
Hivemapper	159,072 contributors	464.27M km mapped, 63,099 mobile hotspots	HivemapperExplorer
Filecoin	1,500+ storage providers	40,392,893 FIL burnt, 1.77 EiB committed capacity	FilecoinExplorer , FilsScanStats
Akash Network	797 active leases	4.99K CPU, 482 GPU, 19.14TB memory, 56.71TB storage	AkashNetworkDashboard
WiFi Map	15M+ contributors	180M+ users, active WiFi hotspots	WiFiMapOfficial
RENDER	93,212 holders	5600 nodes; 408,983 RENDER burned	RenderStats
Golem	204 Providers	19,517 CPU cores, 2771 GPUs	Golem
AIOZ Network	277,810 DePINs	13,806.8 TB data delivery; 277,813 edge nodes	AIOZEcosystem
Bittensor	202,715 active accounts	Total staked: 5,864,261; 224,956 accounts	BittensorScan
Fetch.ai	91 validators	Voting power: 411.79 m FET	Fetch.aiExplorer
Aethir	400,000+ enterprise GPUs	Supported in 95 countries; 99.99% uptime	Aethir
Node AI	792 nodes	415 GPUs; 1177 rentals	NodeAIDashboard
Arweave	292,396 addresses	Weave: 279.91 TiB; Network: 114.8 PiB	ViewBlockArweave
origintrail	5327 holders	8,640,442 finalized blocks	OriginTrail
GOEDNET	14,542 miners	RTK Usage: 150,764 GB; 142 countries	GOEDNET
DIMO	173,560 cars	50 unique models	DIMO
Livepeer	100 orchestrators; 2993 delegators	Estimated usage: 4,539,082 min (7d)	LivepeerExplorer
ThetaNetwork	2434 staked nodes	Circulating supply: 1B tokens	ThetaExplorer
Bittorrent	13,337,190 accounts	Total stake: 45,303B BTT	BittorrentScan

governance and funding), and exchange-backed chains like Hoo and HECO.

Transaction data was collected using a combination of automated scripts, API queries, and manual checks through official blockchain explorers. For Ethereum and BSC, Python scripts using the `Web3.py` library retrieved transaction counts directly from nodes, which were cross-checked with public records from Etherscan and BscScan. Solana data was obtained via its RPC API. In some cases, project-specific explorers such as Filfox, Comoscan, or Helium Explorer were used directly, bypassing script-based extraction.

To ensure data reliability, edge cases such as duplicate entries, failed transactions, and internal contract interactions were identified and excluded. This multi-source and cross-verified approach enabled consistent and accurate reporting of blockchain activity across heterogeneous systems.

5.4. Energy consumption

Energy consumption in Decentralized Physical Infrastructure Networks varies considerably depending on the network architecture, hardware needs and other factors that vary from project to project. The

energy cost of a DePIN network is influenced by three main factors: (1) physical device power demands, (2) blockchain infrastructure overhead, and (3) network size, as indicated by device numbers in [Table 14](#). Improving energy efficiency is important, but evaluation should focus on the computing performance rather than just measuring energy input.

5.4.1. Physical device energy profiles

Energy demands fluctuate greatly depending on the function and hardware used across network segments.

Sensor networks. Projects using distributed sensing devices generally require low power consumption. GEODNET, a network of GNSS reference sensing stations, requires its miner hardware to consume less than 10 W of power [38]. DIMO, which operates a vehicle telemetry sensor network using plug-and-play hardware, does not specify a strict watt-level power limit such as GEODNET; however, its open hardware specification recommends very low-power operation, with LoRaWAN-based devices consuming less than 20 mW in active mode and 1.5 mW in sleep mode, reflecting typical IoT-class energy efficiency [39,40]. The Helium network, which offers wireless connectivity through user-operated hotspots, typically consumes between 5W and

Table 15
DePIN projects with contract addresses and transactions.

Project	Network	Contract address	Transactions
Render	Solana	rndrizKT3MK1iimdxRdWabcf7Zg7AR5T4nud4EkHBof	1,000,000+
	Ethereum	0x6de037ef9ad2725eb40118bb1702ebb27e4ab24	781,830
	Polygon	0x61299774020da444af134c82fa83e3810b309991	102,284
Akash Network	Osmosis	ibc/1480B8FD20AD5FCAE81EA87584D269547DD4D436843C1D20F15E00EB64743EF4	22,914,728
	Archway	ibc/C2CFB1C37C146CF95B0784FD518F8030FEFC76C5800105B1742FB65FFE65F873	3,419,675
Golem	Ethereum	0x7dd9c5cba05e151c895fde1cf355c9a1d5da6429	250,726
	Energi	0xf3ff3bf1d1afcbabd98a304482c4099dc953e9a8	9900
Bittensor	EVM	0x1258d60b224c0c5cd888d37bbf31aa5fcfb7e870	107,661
Fetch.ai	Ethereum	0xaea46a60368a7bd060eec7df8cba43b7ef41ad85	859,602
	BSC	0x031b41e504677879370e9dbcf937283a8691fa7f	292,342
Aethir	Solana	Dm5BxyMetG3Aq5PaG1BrG7rByqEMtnkvPNMExfacVk7	7984
	Arbitrum	0xc87b37a581ec3257b734886d9d3a581f5a9d056c	92,918
	Ethereum	0xbe0ed4138121ecfc5c0e56b40517da27e6c5226b	407,048
Node AI	Ethereum	0x1258d60b224c0c5cd888d37bbf31aa5fcfb7e870	106,649
Filecoin	BSC	0x0d8ce2a99bb6e3b7db580ed848240e4a0f9ae153	1,209,850
	HECO	0xae3a768f9ab104c69a7cd6041fe16ffa235d1810	43
	Hoo	0x0bf85d3b0c9ebcc282fde0591882d12e57e700b3	–
Arweave	Arweave	Native	14,903,667,050
BitTorrent	Tron	0x00000000000000000000000000000000000001010	1,139,951
	Energi	0xf1bdcf2d4163adf9554111439dabdd6f18ff9ba7	700
	Ethereum	0xf1bdcf2d4163adf9554111439dabdd6f18ff9ba7	01
	BSC	0x352cb5e19b12fc216548a2677bd0fce83bae434b	207,860
Storj	Ethereum	0xb64ef51c888972c908cfacf59b47c1afbc0ab8ac	2,017,330
	Harmony	0x266f341e33aa61c30c6a9af89314811a5b097cb4	02
	Energi	0xcde71daaffb6a12d584f55777d4c9e9d3c353c1e	10,050
Helium	Solana	hntyVP6YFm1Hg25TN9WGLqM12b12b8TQMcknKrdU1oxWux	2,4050,000+
WiFi Map	Polygon	0xe238ecb42c424e877652ad82d8a939183a04c35f	93,006
Theta Network	Theta	0x3883f5e181fccaf8410FA61e12b59BAAd963fb645	190,609
Orchid	Ethereum	0x4575f41308EC1483f3d399aa9a2826d74Da13Deb	352,429
Livepeer	Ethereum	0x58b6a8a3302369daec38334672404ee733ab239	821,943
	Harmony	0xbd3e698b51d340cc53b0cc549b598c13e0172b7c	02
	Arbitrum	0x2899ba1701c2f088cf0faf8b3705246331cb8a839	90,051
AIOZ Network	Ethereum	0x626e8036deb333b408be468f951bdb42433cbf18	152,578
	BSC	0x33d08d8c7a168333a85285a68c0042b39cf3741d	177,806
HiveMapper	Solana	4vMsoUT2BWatFweudnQM1xedRLfJgJ7hswchpZ4xgBTy	4,459,300+
Origin Trail	Ethereum	0xaa7a9ca87d3694b5755f213b5d04094b8d0f0a6f	221,259
GEODNET	Solana	7JA5eZdCzztSfQbJvS8aVVxMFf81R59VvwnocV1mKHu	211,242

20W per outdoor hotspot at peak load, and had over 950,000 hotspots registered by September 2022, shown in Table 14.

Compute and AI networks. Networks using GPUs for computation and AI tend to have high energy demands, but ongoing hardware and software innovations are quickly boosting efficiency in this field [41]. During Deep Learning (DL) model training, GPUs typically account for most energy use, making up about 61%–73% of total energy [42]. Also, around 60%–80% of AI energy consumption results from running models on live data (inference), rather than from training the models [41]. Compute projects operate at a large scale. Aethir, which pools enterprise-scale GPUs for cloud services optimized for AI and gaming, reports total revenue of \$45.13M since inception [43,44]. It boasts hosting 424,279 CPU cores and over 435,000 GPU containers across more than 200 locations worldwide. Aethir’s decentralized GPU cloud hosting offers bare-metal GPUs up to 86% cheaper than alternatives for NVIDIA H100 inference [43,44].

Storage networks. Decentralized storage networks such as Filecoin and Arweave rely on physical infrastructure like hard disks and solid-state drives for distributed data storage [43]. Arweave employs a novel blockweave architecture for permanent data storage, secured by an endowment model [43]. Filecoin functions as a storage marketplace that depends on cryptographic proofs and economic incentives [43].

5.4.2. Blockchain infrastructure overhead

The blockchain’s consensus mechanism greatly influences energy consumption. Proof-of-Stake (PoS) is broadly seen as more energy-efficient than Proof-of-Work (PoW) [38]. GEODNET uses PoS for transaction validation. Its consensus protocol combines external geospatial data input (Proof of Location and Proof of Accuracy) with staked tokens (PoS) to efficiently determine block generation [38]. Many leading DePIN projects, including Render Network, Hivemapper are built on the Solana blockchain platform [40,43].

6. Open challenges and future directions

The ongoing expansion of DePINs necessitates a systematic approach to addressing fundamental issues, including economic stability, cross-chain scalability, verification reliability, infrastructure equity, regulatory compliance, and security. Managing these challenges is essential for DePINs to transcend niche uses and serve as a foundational layer for community-owned infrastructure networks.

6.1. Tokenomic stability and reward dynamics

Long-term success depends on creating resilient tokenomic models. Price volatility in tokens causes uncertainty, discouraging investment and leading to participant withdrawal during downturns [32].

Conversely, high volatility can make network services more expensive for users if token prices spike [32]. Modular DePIN structures aim to address this by allowing economic models tailored to specific modules, but designing sustainable token economies for each remains a key research area [10]. Effective tokenomics should foster a self-reinforcing cycle where higher demand boosts token value, incentivizing infrastructure contributions and stability [32].

6.2. Cross-chain interoperability and ecosystem fragmentation

Efficient multi-blockchain DePIN ecosystems require seamless interoperability to enable communication and state transfers across different chains [9]. While solutions like LayerZero and Wormhole expand access, they also fragment liquidity [19]. Modular infrastructure's key feature, composability, lets developers combine modules from various providers to build comprehensive DePIN applications [10,45]. Critical research is needed on how nodes in different modules can authenticate and communicate securely to preserve this composability [10].

6.3. Scalable trust, verification, and oracle dependence

Building trust is vital since token issuance depends on verifiable real-world data [8]. Handling large volumes of sensor data requires off-chain computing, but proving the integrity of this data on-chain is challenging [8,21]. Cryptographic tools like Zero-Knowledge Proofs (ZKPs) and hardware solutions like Trusted Execution Environments (TEEs) help ensure confidentiality and integrity [21]. However, applying ZKPs to AI models (ZKML) can be computationally intensive up to 100,000 times more than traditional computation, making TEEs a more practical choice for off-chain AI workloads [8]. Overcoming the trust issues among geographically dispersed nodes without centralized control remains an open challenge [8].

6.4. Environmental sustainability and hardware lifecycle

The surge in demand for high-performance computing driven by the race toward Artificial General Intelligence (AGI) raises environmental concerns [35]. This competition has led to a scramble for GPU chips and secure energy contracts, including future nuclear power, to meet their computing needs [19]. Connecting new power plants to existing grids also presents fundamental infrastructure challenges that must be addressed to prevent stagnant energy consumption from hindering progress [19]. DePIN projects promote solutions such as Proof-of-Flexibility (PoF) consensus, rewarding devices for offering flexible energy capacity [19], and protocols that incentivize solar farms to generate carbon credits with auction revenues used for token burns [19].

6.5. Governance, decentralization, and participation

Despite DePIN's decentralized intent, governance structures vary widely, from hierarchically organized core teams to active community voting mechanisms [14]. Often, community participation in governance proposals is non-binding, limiting direct influence on core parameters or legal entities [14]. Formal governance structures define key elements like voting objects (parameters or proposals), participation rules, and voting methods (single choice, ranked-choice) [14]. Systems like IoTeX use vote-escrow models (veIOTX) within their Marshall DAO to ensure governance reflects the interests of committed stakeholders [8].

6.6. Geographic disparities and infrastructure equity

DePIN aims to enable the next 5 billion crypto owners to earn their first crypto, utilize universal human capabilities such as time and intelligence to counteract wealth concentration [19]. The scarcity of GPUs contributes to an AI wealth gap between GPU-rich (big tech) and GPU-poor (smaller entities and the public) [35]. Solutions involve aggregating enterprise GPUs into global networks to provide affordable, on-demand compute, thus addressing this gap [35]. Additionally, governments like Tanzania are using DePIN to develop local digital identity systems on domestic computing resources [19].

6.7. Regulatory and legal uncertainties

The Decentralized and anonymous nature of DePINs poses regulatory challenges, complicating oversight of fund flows and increasing the risk of illicit activities such as money laundering [9]. Regulatory sandboxes, such as those led by the UK FCA, are crucial for experimentation and the development of frameworks. A key legal issue involves GDPR's Right to be Forgotten; personal data embedded in AI model parameters complicates full erasure after training [26].

6.8. Security and attack surfaces in hybrid networks

DePINs integrate cyber and physical components, forming complex attack surfaces such as device tampering, spoofing, supply chain breaches, malware, and cyber threats like vulnerabilities in smart contracts [9]. The vulnerability of centralized infrastructure systems is highlighted by past hacks and deepfake attacks, emphasizing the necessity for Decentralized security solutions [19]. These include hardware-based security primitives like TEEs and ZKPs, AI-driven real-time monitoring, anomaly detection, and governance-based penalties to reduce risks from malicious insiders [8,21,26].

6.9. Future research

Future research on DePIN systems needs to address eight inter-related issues, beginning with the design of flexible, adaptive inflation schedules and resilient reward models to maintain tokenomic stability, guided by Helium's insights; developing secure cross-chain bridging protocols to ensure interoperability without double-counting, while preserving geospatial and temporal metadata; designing decentralized oracle architectures for scalable trust and verification, employing hardware-assisted attestation and exploring efficient zkVM alternatives; evaluating energy use and e-waste throughout the lifecycle for environmental sustainability, with incentives for renewable energy; improving governance and participation to boost voter turnout and reduce power concentration via quadratic voting and hybrid approaches; addressing geographic disparities by expanding coverage in underserved areas; establishing regulatory compliance frameworks with sandbox experiments and automated systems; and developing cyber-physical security threat models that account for both digital vulnerabilities and physical tampering.

Furthermore, future research should perform comprehensive comparative analyses of energy consumption and latency metrics across various DePIN projects, since these performance indicators differ greatly depending on factors such as hardware setups, consensus algorithms, network structures, and application areas. Implementing standardized benchmarking methods would facilitate more meaningful cross-project comparisons and help guide optimization efforts.

7. Threats to validity

This study faces potential threats to validity that may limit the generalizability and reliability of our findings. We acknowledge these limitations and outline the measures taken to mitigate their impact.

7.1. Internal validity

Data source consistency. Our analysis draws on data from multiple sources (DePIN Scan, DePIN Hub, CoinGecko, Coin MarketCap, DePIN Ninja, Messari, GitHub API, blockchain explorers) that differ in collection methods and verification standards. While we cross-referenced sources where applicable and documented discrepancies (as shown in Table 4), some inconsistencies remain. To mitigate this, we prioritized on-chain verifiable data and reported the provenance of each metric.

Temporal alignment. Data collection occurred across different time periods (February–June 2025), which may affect cross-project comparisons due to the volatility of cryptocurrency markets and evolving project metrics. We addressed this by specifying collection dates for major datasets and focusing on structural characteristics rather than values at specific points in time.

Self-reported metrics. Some statistics rely on self-reported data from project dashboards and documentation. We mitigated this by prioritizing independently verifiable metrics (e.g. on-chain activity, GitHub statistics) and cross-validating data where possible.

7.2. External validity

Selection bias. The market capitalization threshold of \$5 million may bias the sample towards more mature projects and underrepresent smaller or emerging initiatives. This could limit the generalizability of our architectural framework to the broader DePIN ecosystem. However, the selection ensures coverage of economically significant and operationally active projects, providing insight into widely adopted implementation patterns.

Geographic concentration. The concentration of 68.5% of DePIN devices in Asia may influence the generalizability of our observations. Nonetheless, our analysis focuses on technical architectures and economic models that are largely independent of geographic context.

Temporal snapshot. Our findings represent a snapshot of a rapidly evolving ecosystem. The number of DePIN projects has increased from approximately 100 in 2022 to over 1200 in 2024. As such, architectural patterns may continue to change. We address this by focusing on fundamental structural elements likely to persist across project generations.

7.3. Construct validity

DePIN definition ambiguity. The term DePIN, introduced in 2022, is used inconsistently across projects. Our analysis found that 10 out of 21 projects do not explicitly identify as DePIN, despite exhibiting relevant technical characteristics. We mitigated this by defining clear inclusion criteria based on project structure rather than self-identification, and by verifying classification using multiple specialized sources.

Metric interpretation. Some indicators (e.g. GitHub stars, transaction counts) may not fully reflect the intended constructs such as project health or user engagement. To address this, we used multiple complementary metrics and focused on consistent patterns across projects.

7.4. Conclusion validity

Sample size. Although our analysis of 21 projects covers key DePIN categories and market segments, it represents only a small proportion of the estimated 1200+ projects. However, the selected projects account for a substantial share of the ecosystem's market capitalization and activity, supporting the relevance of the sample.

Architectural generalization. The six-layer architecture proposed in this work is derived from observed patterns across the selected projects. While we validated this framework against all 21 cases (Table 8), its applicability to future or structurally different DePIN systems remains an open question. We present it as a descriptive model for current implementations, not a prescriptive standard.

Causal inference limitations. This study is descriptive in nature and does not aim to establish causal relationships between architectural choices and project outcomes. Correlations between technical design and market performance should not be interpreted as causation without further longitudinal research.

Despite these limitations, this study offers the first survey of DePIN architectures and implementations across multiple categories. It contributes to an emerging area by providing structure and reference points for future empirical and theoretical research. Broader sampling, time series analysis, and experimental studies are needed to refine and extend the findings presented here.

8. Conclusion

This study has examined the Decentralized Physical Infrastructure Network (DePIN) phenomenon in response to three guiding research questions.

In relation to RQ1, we defined the core characteristics of DePIN systems. Although the term was formalized in 2022, the concept dates back to early projects from 2013–2014 that applied blockchain to physical infrastructure. The number of DePIN initiatives has grown rapidly, from around 100 in 2022 to an estimated 1200 by 2024. A substantial portion of physical deployments (68%) are located in Asia, followed by Europe. Despite this growth, academic research on DePIN remains limited, with only a small number of peer-reviewed studies published to date.

For RQ2, we identified a layered architecture common to DePIN systems, composed of a physical layer, verification mechanisms, oracles for off-chain data, a blockchain execution layer, a reward distribution system, and a user redemption interface. Unlike previous categorizations that focus on application domains, our framework emphasizes the nature of shared physical resources and defines six main categories: Sensor, Compute, Wireless, AI, Storage, and Bandwidth networks.

Addressing RQ3, we analyzed 21 active DePIN projects based on their classification and market capitalization. Most of these projects are open-source and differ in their strategic priorities regarding market entry and codebase release timelines. Many operate across multiple blockchain platforms, primarily Ethereum and Solana, but also employ specialized chains tailored to specific infrastructural needs.

This study contributes to the emerging academic discussion on DePIN by clarifying its defining traits, proposing a general architectural model, and providing an overview of key operational projects within the ecosystem.

CRediT authorship contribution statement

Azmat Ullah: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Investigation, Formal analysis, Data curation. **Andrea Pinna:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Methodology, Investigation, Conceptualization. **Maria Ilaria Lunesu:** Writing – review & editing, Methodology. **Giuseppe Destefanis:** Writing – review & editing, Validation, Methodology, Investigation. **Roberto Tonelli:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Conceptualization.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this manuscript, the authors used language models provided by the privacy-preserving Duck.ai service to assist with readability and linguistic refinement. All content was subsequently reviewed and edited by the authors, who take full responsibility for the final version of the article.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This work was partially supported by the project SERICS (PE00000014) under the MUR National Recovery and Resilience Plan, funded by the European Union–NextGenerationEU.

This work was partially funded by the Ministero dell'Università e della Ricerca (MUR), under issue D.M. 118/2023 Borse di Dottorato—Dottorato di Ricerca di Interesse Nazionale in Blockchain e Distributed Ledger Technology, as part of the National Recovery and Resilience Plan.

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