

Article

# Increasing the Efficiency of CO<sub>2</sub> Markets for Residential Consumers with Blockchain Solutions: An Empirical Investigation

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## Abstract

Recent studies highlight blockchain's potential to enhance residential energy efficiency by enabling traceable, verifiable, and incentivized household actions. This research focuses on optimal organizational models, technology choices, and measurement systems needed to support carbon reduction at the residential level through blockchain. To do so, a multiple-case study was conducted, analyzing six companies that leverage blockchain in the context of carbon markets. Data have been collected through direct, semi-structured interviews with informants from each company. Results from the six cases have been analyzed through a cross-case comparison and clustered to identify three different archetypes of business ecosystem. The results suggest that blockchain supports residential energy efficiency and carbon markets through behavioural incentives, infrastructural integration and hybrid measurement, and reporting and verification systems. They also indicate that blockchain effectiveness depends less on specific protocols than on aligning technological design, governance, and ecosystem context across civic, financial, and institutional models.

**Keywords:** blockchain; sustainability; decarbonization

## 1. Introduction

Blockchain has emerged as a foundational infrastructure capable of reshaping the way in which data is recorded, verified, and shared across distributed networks. While originally developed to support cryptocurrencies, its core features (i.e., decentralization, immutability, transparency and programmability) have made it an increasingly attractive solution for a broad range of applications that require secure, tamper-resistant, and trustless data environments. Among these applications, blockchain is gaining traction in environmental governance, climate policy, and energy systems, especially as global efforts intensify to decarbonize the economy and engage all sectors of society in climate action [1–3].

In the environmental and energy sectors, smart contracts facilitate the automation of verification processes related to energy savings, reward distribution, and emissions tracking, tasks historically reliant on costly, centralized third-party verification systems [4]. This automation capability represents a significant advancement in reducing transaction costs and increasing operational efficiency across various environmental applications.

The increasing urgency to address climate change has led to the development of various mechanisms to reduce greenhouse gas emissions, among which carbon credit markets play a central role. Carbon markets can include carbon credits and carbon offset. A



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carbon credit represents the right to emit one metric ton of carbon dioxide or an equivalent amount of other greenhouse gases such as methane or nitrous oxide. A carbon offset represents the removal of one metric ton of carbon dioxide or an equivalent amount of other greenhouse gases from the atmosphere. These credits serve as financial instruments that support projects designed to reduce or remove greenhouse gas emissions from the atmosphere, including renewable energy generation, afforestation, reforestation, and energy efficiency improvements [5].

The process underpinning carbon credit markets involves certifying emission reductions through standardized methodologies, ensuring the authenticity and additionality of each credit, thus verifying that the reductions would not have occurred without the project intervention [6]. Once certified, these credits are issued and traded, enabling companies or individuals to offset their emissions by purchasing credits generated from verified projects. Consequently, carbon credits incentivize emission reductions while attracting investments into sustainable initiatives.

This comprehensive overview underscores the complexity of carbon credit markets and energy efficiency initiatives, revealing both their potential and their vulnerabilities. The integration of emerging technologies, such as blockchain, promises to address systemic challenges, particularly by enhancing transparency, verification, and participation. Against this backdrop, the present research proceeds to analyze these dynamics to offer deeper insight into the mechanisms driving market efficiency, user engagement, and innovation adoption.

Despite the growing interest, empirical evidence on how blockchain-based systems are actually designed and implemented in climate- and energy-related contexts remains fragmented. This study is motivated by the need to move beyond conceptual promise and examine how these technologies function in practice, particularly at the residential level where participation, verification, and governance challenges are most pronounced.

The recent literature on blockchain applications in the environmental and energy sectors has increasingly emphasized the potential of distributed ledger technologies to support low-carbon transitions at the household level. Residential users are seen not only as energy consumers but also as potential contributors to energy savings and carbon mitigation strategies [7]. However, the effectiveness of such participation hinges on systems capable of ensuring traceability, verifiability, and incentivization of individual behaviours, requirements that are often poorly addressed by traditional policy instruments. Blockchain-based systems, owing to their decentralization, programmability, and transparency, are increasingly proposed as tools to address these limitations. Several recent contributions examine how blockchain can enable peer-to-peer energy exchanges [8], support domestic carbon credit schemes [9] or automate energy performance contracts at the residential level [10]. These applications are unified by a shared concern: how to translate individual behaviours into measurable, verifiable, and tradable contributions to energy efficiency and emissions reduction.

Despite the growing body of the literature on blockchain applications in energy and environmental domains, three major gaps remain. First, existing studies largely focus on conceptual frameworks or single-use cases, offering limited empirical evidence on how blockchain systems are actually designed and governed in real-world residential contexts. Second, prior research often emphasizes technological potential, while underexploring the organizational models and ecosystem configurations that shape user participation and system effectiveness. Third, the literature treats measurement, reporting, and verification (MRV) primarily as a technical issue, without sufficiently addressing how hybrid on-chain/off-chain verification architectures operate in practice. This study addresses these gaps by providing a comparative, multi-case empirical analysis of six blockchain-based initiatives operating in residential and consumer-facing carbon and energy markets.

Accordingly, this study aims to generate empirically grounded insights into how blockchain supports residential energy efficiency, which organizational and technological models are most coherent, and how MRV systems can be structured to enhance the credibility of CO<sub>2</sub> markets. This leads to the first research question (RQ):

**RQ1:** *How can blockchain help reduce the energy consumption of residential users?*

However, this RQ can be further detailed in two different directions. First, the design of the organizational model underpinning a blockchain-based system is a decisive factor in determining its efficacy, sustainability, and coherence, particularly when such systems aim to address complex socio-technical challenges such as residential energy efficiency. This leads to the first sub-research question (RQ1a):

**RQ1a:** *What can be the most coherent organizational model of a blockchain-based system to promote energy efficiency at the residential level?*

The answer lies not merely in selecting a blockchain type, but in critically evaluating the interplay among governance mechanisms, stakeholder engagement, data management, and regulatory alignment.

The choice of blockchain technology is a critical design decision in developing systems aimed at enhancing energy efficiency at the residential level. While blockchain is often discussed in terms of its general features (i.e., immutability, decentralization, transparency, and automation), the specific technological configurations of blockchain systems greatly influence their effectiveness in real-world applications. In particular, decisions regarding consensus mechanisms, data structures, smart contract capabilities, scalability, and interoperability directly affect a system's capacity to handle high transaction volumes, ensure data integrity, protect user privacy, and support automated processes for energy monitoring and incentive mechanisms. These technical aspects are not neutral; rather, they embed specific affordances and constraints that must be aligned with the practical, regulatory, and behavioural demands of residential energy efficiency programmes. These aspects lead to the second sub-research question (RQ1b):

**RQ1b:** *What can be the most effective technology choice to implement a blockchain-based system to promote energy efficiency at the residential level?*

In both compliance and voluntary carbon markets, the credibility and effectiveness of emissions reductions hinge on the robustness of MRV systems. MRV mechanisms are the backbone of carbon and energy efficiency markets, serving as the interface between physical interventions and the generation of quantifiable, tradable climate benefits. A reliable MRV system ensures that environmental claims are accurate, additional, and non-duplicated, enabling the transformation of decentralized actions into credible environmental assets [8,11]. In the residential sector, however, MRV poses particularly acute challenges. The decentralized and small-scale nature of household interventions makes data collection and validation both logistically complex and economically inefficient. This leads to the second research question (RQ2):

**RQ2:** *How can measurement and verification activities be organized to address the inherent limitations of the CO<sub>2</sub> market?*

Overall, the literature demonstrates strong theoretical consensus on blockchain's potential for supporting sustainability transitions, yet remains fragmented across technical, economic, and policy-oriented streams. Empirical studies are scarce, particularly those adopting a comparative, ecosystem-level perspective. Most existing works either analyze single pilot projects or focus narrowly on specific applications such as peer-to-peer trading or tokenized offsets. As a result, there is limited understanding of how different blockchain

configurations, governance models, and MRV systems interact in shaping real-world performance and scalability.

This article contributes to the literature in three main ways. First, it provides one of the few empirical, multi-case analyses of blockchain applications in residential and consumer-oriented carbon markets. Second, it adopts an ecosystem perspective, integrating organizational, technological, and institutional dimensions through the 6C framework. Third, it advances the debate on digital MRV by identifying hybrid verification architectures that combine algorithmic integrity with institutional legitimacy. Together, these contributions move beyond conceptual promise and offer grounded insights into how blockchain can effectively support climate action.

## 2. Methodology

This study adopts a qualitative, exploratory design guided by abductive reasoning. This epistemological orientation is especially appropriate for investigating emergent technologies, where theoretical frameworks remain in flux and empirical realities are rapidly evolving. The research design is anchored in a multiple case study approach, which enables an in-depth exploration of blockchain integration across diverse organizational contexts. Drawing on the work of Eisenhardt and Graebner [12], this study treats each case as a potential contributor to theoretical development. The analysis focuses on identifying patterns across cases to uncover emergent constructs, explore interrelationships, and refine conceptual frameworks grounded in empirical evidence.

Case selection was guided by a theoretical sampling strategy intended to maximize analytical insight rather than statistical generalizability [13]. A key consideration in the selection process was the focus on organizations operating at least partially within the business-to-consumer (B2C) segment. This focus is particularly relevant for understanding how blockchain technologies interact with end-user behaviour, a critical factor in designing effective incentive structures for energy efficiency and carbon mitigation. The process involved a structured, multi-step screening procedure to ensure alignment with the research objectives. A pool of approximately forty potential cases was initially identified through a systematic review of publicly available sources, including white papers, company websites, and project documentation. These cases spanned a diverse array of applications, including blockchain-enabled carbon credit platforms, Decentralized autonomous organizations (DAOs), tokenized energy systems, microgrid implementations, and data-sharing infrastructures. This broad initial scope was essential for capturing the heterogeneity of blockchain innovation in the sustainability domain [14]. From this pool, theoretical sampling was used to narrow the pool to twelve candidates that best matched the research focus, ensuring relevance to residential or B2C contexts, technological and business-model diversity and adequate data accessibility. Finally, a feasibility check retained only organizations willing to participate in interviews and able to provide sufficient supporting material, resulting in the final six case studies: Allinfra, Codos, Coorest, Hestro, KlimaDAO, and StromDAO.

Given the novelty of the intersection of blockchain and carbon market, many of the identified organizations were small-scale and in the early stages of development, often with limited human resources. This reality posed challenges for data collection, particularly in securing multiple informants per case, which is typically recommended in case-based research [12]. To address this limitation, the study adopted a broader set of cases than is customary in comparable research designs, thus compensating for limited within-case depth through greater cross-case variation. This strategic choice aligns with Yin's [15] emphasis on analytic generalization in the context of exploratory research, especially in emerging fields.

### 2.1. Data Collection

Empirical data were collected through a triangulated strategy that combined qualitative interviews with extensive documentary analysis, thereby enhancing the study's depth, validity and contextual sensitivity. The primary data source consisted of semi-structured interviews with key stakeholders in each selected case. To address the limitations inherent in single-informant interviews (as is proved challenging to secure multiple informants per organization in limited personnel companies), email surveys and asynchronous exchanges were employed to supplement interview data. Moreover, the study incorporated a substantial body of secondary data. This included technical white papers, platform documentation, policy briefs, official websites, public presentations, and, where available, video content such as webinars and product demonstrations.

The analytical process employed a hybrid coding approach that integrated both deductive and inductive elements. Deductive codes were informed by the existing literature on blockchain technology, digital governance, and carbon market regulation [16–18]. Concurrently, inductive themes emerged organically from the empirical material during the data immersion process. Qualitative data analysis software facilitated the organization of codes and themes across cases.

The interview guide was structured in two tiers: an initial phase to build rapport and gather general background on the organization, followed by a more focused set of questions directly linked to the RQs, covering governance, token economics and technical implementation. All interviews were conducted remotely and recorded with informed consent (see Table 1). The interview guide used during the interviews is available in Appendix A.

**Table 1.** Organizations interviewed.

Organization	Country	Interview Dates
Allinfra	China	25 June 2024, 10 September 2024
Codos Foundation	Switzerland	23 May 2024, 4 July 2024
Coorest	Netherlands	18 May 2024, 14 October 2024
Hestro	Italy	17 July 2024, 17 July 2024
KlimaDAO	n.a. (global)	30 April 2024, 10 May 2024
StromDAO	Germany	26 June 2024

### 2.2. Data Analysis

The qualitative data gathered for this study were analyzed using a structured, multi-phase process. First, each case was examined individually to reconstruct its operational logic and business model. This involved identifying key elements, including value proposition, customer segment, technological setup, governance mechanisms, incentive structures, and environmental goals. The goal was to create an internally consistent account of how blockchain was implemented within a specific organizational, institutional, and technological context. To represent it, the authors developed the Business Model Canvas for each company in the analysis, which is represented in Tables 2–7.

Second, a comparative analysis was conducted to identify broader patterns in how blockchain technologies are operationalized across diverse contexts. This step moved beyond reconstructing of individual business models to examine differences in value-creation logics, technological configurations, governance structures, stakeholder targeting and environmental positioning.

Third, the 6C framework [19] was applied to each case to structure a systemic understanding of how blockchain-enabled platforms configure and evolve within their respective

ecosystems. The 6C framework enables a holistic analysis of ecosystems as dynamic systems composed of multiple interdependent elements. It comprises six dimensions, each addressing a specific facet of how ecosystems are formed, stabilized, and transformed over time:

1. Context focuses on the external environment in which the ecosystem is embedded, including regulatory structures, institutional forces, and lifecycle dynamics. It helps explain why certain configurations emerge and how actors respond to complexity and uncertainty.
2. Construct refers to the structural and infrastructural foundations of the ecosystem, identifying the core elements that support system-wide functioning.
3. Configuration examines the pattern of relationships among actors, the design of value flows, and the integration of roles and processes within the ecosystem.
4. Cooperation investigates the interaction and governance mechanisms through which ecosystem members align their interests and coordinate activities toward shared strategic objectives.
5. Capability encompasses the functional competencies developed by actors within the ecosystem, such as adaptability, innovation capacity, and the ability to manage complexity and achieve synergies.
6. Change reflects the dynamic nature of the ecosystem, focusing on how configurations evolve over time, how systemic transformations occur, and how organizations reposition themselves in response to external shifts.

Finally, the Gioia methodology [20] was employed to generate abstract conceptual categories across cases. Interview transcripts and secondary materials were coded iteratively: first-order codes were derived directly from participants' language, then grouped into second-order themes and finally synthesized into aggregate dimensions. This process yielded a set of theoretically relevant constructs (such as "digital behaviour orchestration" and "trust through token logic") that emerged organically from the data and offered analytical leverage across the case set.

The data analysis followed a step-by-step coding process combining the Gioia method with the 6C framework. Interview data were first coded into clearly defined first-order concepts grounded directly in repeated and explicit interview statements (e.g., public-chain verifiability, CO<sub>2</sub> token-burn mechanisms, NFTs as proof objects, and friction-light onboarding). These concepts were then clustered into second-order themes (e.g., "Technological reliability and auditability" and "User-centric blockchain design") based on their functional role (in this case, the former identified as the primary driver of climate transparency, indicated by a solid link, and the latter as a supporting enabler, indicated by a dashed link). The study used a single-coder design with no formal inter-coder reliability test; instead, dependability was ensured through a living codebook with inclusion rules and quote anchors, repeated quote-to-code audits to prevent drift, reflexive memos to resolve ambiguities, and systematic coherence checks when rolling first-order concepts into higher-level themes.

This layered analytical architecture was grounded in a rigorous coding procedure. Interview data were transcribed using LiGRE software (V. 5.0.7) to ensure accuracy, then reviewed and cross-checked against field notes to preserve contextual nuance. Open coding was conducted line by line, generating short descriptive labels for each segment. These codes were then grouped into broader conceptual categories to identify emergent patterns and thematic linkages. As categories stabilized, they were linked back to the research questions, ensuring analytic alignment and interpretive coherence. The final step of the analysis synthesized findings across all levels into a generalizable interpretive framework for understanding the emerging landscape of blockchain-enabled sustainability platforms.

### 3. Results

The following subsections present the six individual case studies, drawing on this multi-layered approach to highlight both intra-case specificity and inter-case patterns.

#### 3.1. Codos Foundation

The Codos Foundation, a Swiss-based non-profit organization, is dedicated to mitigating global carbon dioxide emissions by promoting sustainable commuting behaviours. By encouraging alternatives to private car use, Codos aims to foster lasting changes in individual mobility patterns, thereby contributing to broader climate and sustainability goals. At the core of Codos' operational model is the integration of blockchain technology to support its incentive and reward mechanisms. Embedded within the Codos mobile application, this system uses smart contracts to verify users' environmentally friendly transportation choices (such as walking, cycling, or public transit) and automatically issue digital rewards in the form of Codos Tokens. These tokens are minted when smart contracts are triggered by authenticated low-emission activities, creating a secure, traceable, and transparent link between user behaviour and the incentives provided. The use of a decentralized ledger ensures that all transactions are immutable and verifiable, reinforcing the platform's integrity and trustworthiness. As one interviewee described, "*Codos is a system that allows commuters to automatically and privately track their transport habits and tokenize their CO<sub>2</sub> savings.*" Interviewees also emphasized the hybrid nature of the Codos Token, which functions as both a utility token and a payment token capable of circulating externally. One participant explained, "*It's not just a points system or a voucher, but a real digital asset that can be traded on exchanges or used as a payment method with merchants.*" This dual functionality distinguishes Codos from conventional mobility rewards programmes, which typically rely on centralized, discount-based incentives.

A key innovation in the app is the CO<sub>2</sub> Avoidance Calculator, which quantifies emissions reductions for each journey. Codos Tokens can be redeemed for eco-friendly goods and services within the Codos Ecosystem, creating a closed-loop system that aligns personal incentives with environmental values. This model not only reinforces behavioural change but also supports the emergence of a value-driven user community. In this context, trust is not merely a functional requirement but a foundational principle critical to the legitimacy and scalability of blockchain solutions in the sustainability sector.

Despite these technical achievements, interviewees acknowledged several unresolved challenges. Chief among them is the issue of token valuation and economic sustainability. While the technical creation of an ERC-20 token is relatively straightforward, ensuring that the token maintains real and stable value is significantly more complex. As one participant remarked, "*Creating an ERC-20 token is easy, but giving it real value is the real challenge*". This statement underscores the necessity of a carefully designed economic model, one that mitigates volatility, resists speculative pressures, and maintains long-term user trust and engagement. Finally, regulatory uncertainty emerged as a critical concern. The classification of the Codos token has direct implications for legal compliance, particularly with respect to Know Your Customer and Anti-Money Laundering requirements. One interviewee observed, "*Depending on whether our token is classified as a utility, payment, or security token, we must adopt different compliance measures*". This challenge reflects the broader ambiguity inherent in blockchain-based incentive systems, particularly when tokens are intended to function as transferable digital assets with real-world economic value.

Table 2 represents Codos Foundation's business model within the Business Model Canvas framework [21].

**Table 2.** Business Model Canvas for Codos Foundation.

<b>Key Partnerships</b> Blockchain and ML tech providers Sustainable product vendors Government agencies Environmental NGOs Corporate and public transit partners	<b>Key Activities</b> Tech development and optimization ML model training for transport detection User acquisition and engagement Regulatory compliance Strategic partnership management	<b>Key Resources</b> Codos app & blockchain infrastructure ML algorithms & CO <sub>2</sub> calculator Developer & sustainability expert teams Regulatory expertise Financial and institutional support
<b>Value Propositions</b> Real-time CO <sub>2</sub> savings tokenization Transparent, trust-based rewards Gamified sustainability engagement Access to green marketplace Personalized CO <sub>2</sub> tracking		
<b>Customer Relationships</b> Community building features Personalized insights Regular challenges & updates Multi-channel support User feedback integration	<b>Channels</b> Codos mobile app Website and social media Partnerships with public/private entities Events and workshops	<b>Customer Segments</b> Individual urban commuters Eco-conscious users Companies promoting green mobility Vendors of sustainable goods Municipal/government stakeholders
<b>Cost Structure</b> App and blockchain infrastructure ML model development Staff and operational costs Marketing and outreach Compliance and legal expenses Incentives and liquidity pool	<b>Revenue Streams</b> Grants and donations Vendor commissions Eco-brand sponsorships Data analytics services Potential token-based revenue	

### 3.2. KlimaDAO

KlimaDAO is a global DAO with no central headquarters. Its mission is to improve transparency, accessibility, and efficiency within the voluntary carbon market through the strategic application of blockchain and Decentralized Finance (DeFi) technologies. The organization positions itself as a corrective to the legacy carbon market infrastructure, which has long been criticized for its opacity, inefficiency, and reliance on costly intermediaries. As one interviewee explained, “The purpose of KlimaDAO was to use blockchain technologies to improve the market conditions within the voluntary carbon market”. To achieve this, KlimaDAO leverages the Polygon PoS network, a scalable, Ethereum-compatible blockchain selected for its low transaction fees and high throughput. According to a representative, “We chose to launch on Polygon PoS, which is a high-scale Ethereum roll-up that’s quite battle-tested.” This

infrastructure enables the organization to manage high transaction volumes efficiently while providing flexibility to explore future cross-chain expansion.

A defining innovation of KlimaDAO is its use of DeFi mechanisms, particularly automated market makers and liquidity pools, which enable decentralized, transparent pricing of carbon credits. This approach aims to replace the traditional over-the-counter model with open-source, permissionless access to carbon credit markets. One interviewee emphasized the impact of this shift: *“Instead of you having to execute deals over-the-counter and negotiate prices bilaterally, you can just come and use our smart contracts.”* These smart contracts automate transactions and provide liquidity to the carbon market, making it accessible to a broader range of participants.

KlimaDAO’s tokenization framework supports multiple types of carbon assets. Some carbon credits are natively issued on-chain as ERC1155 tokens, requiring no further processing. Others follow a hybrid structure in which off-chain credits are represented on-chain as ERC721 tokens and then divided into ERC20 tokens to enhance liquidity and usability. This layered architecture reflects a strategic effort to balance traceability with tradability in a digital environment.

However, KlimaDAO does not directly conduct MRV of carbon credits. Instead, it relies on third-party standards such as VERRA and the Gold Standard. As one interviewee acknowledged, *“We rely on trusted third parties and industry-standard registries to maintain that MRV process and ensure that the projects are verified.”* While this limits KlimaDAO’s vertical integration, it also underscores its current focus on infrastructure and market design. Nonetheless, the organization has expressed a clear interest in collaborating with digital MRV providers that use satellite imagery, IoT devices, and AI analytics to further integrate on-chain and off-chain data.

Governance at KlimaDAO is rooted in its community of token holders, who participate in a structured decision-making process that includes forum-based discussion, polling, and token-weighted voting via Snapshot. *“Klima token holders have the right to vote on proposals,”* an interviewee noted, *“those proposals are posted on our governance forum where they’re discussed and debated, and then we have a Snapshot instance where people vote.”* While this model embodies the ethos of decentralization, it also reveals operational trade-offs. As another contributor pointed out, *“There is a trade-off between running a decentralized organization and being able to build high-quality software products.”* To address this challenge, KlimaDAO has externalized certain development activities into a more traditionally structured entity, allowing for faster implementation while maintaining DAO oversight. A further limitation discussed in the interviews relates to the broader scalability of blockchain-based carbon infrastructure. Although Polygon provides high throughput, network congestion can still result in elevated costs. Still, interviewees reported no major technical bottlenecks thus far, and future plans include exploring higher-performance chains and interoperability solutions. More importantly, several participants emphasized the inadequacy of existing carbon market infrastructure to address the scale of the climate crisis. As one put it, *“The entire voluntary carbon market to date has only issued about 2 billion tons of carbon credits, but we’ve emitted about 2 trillion tons of carbon dioxide since the Industrial Revolution.”* This gap underscores the need for scalable, transparent digital infrastructures, such as those envisioned by KlimaDAO to facilitate widespread participation and impact.

Table 3 represents KlimaDAO’s business model within the Business Model Canvas framework.

**Table 3.** Business Model Canvas for KlimaDAO.

<b>Key Partnerships</b> Carbon standards bodies (e.g., VERRA, Gold Standard) DeFi exchanges and infrastructure providers Tech partners for digital MRV (e.g., IoT, satellite data firms) Environmental NGOs and sustainability coalitions Blockchain developers and crypto community stakeholders	<b>Key Activities</b> Platform and smart contract development and maintenance Tokenization of carbon credits Facilitation of DAO governance processes Operation of AMMs and CarbonMark marketplace Partnership outreach and integration	<b>Key Resources</b> Blockchain and smart contract infrastructure (Polygon POS) Tokenized carbon credit assets Skilled human capital (developers, engineers, community leads) DAO governance framework and engaged community Partnerships with standards bodies and tech providers
<b>Value Propositions</b> Transparent and traceable carbon credit system via blockchain Lower barriers to entry by eliminating intermediaries Enhanced liquidity through automated market makers and liquidity pools Decentralized governance through DAO mechanisms Cost-effective infrastructure compared to traditional carbon markets Innovative integration of blockchain in climate and sustainability initiatives		
<b>Customer Relationships</b> Active community governance through DAO participation Trust through open-source infrastructure and transparent records Educational support with guides and FAQs Direct customer service through online channels	<b>Channels</b> Polygon POS blockchain platform Decentralized exchanges (e.g., SushiSwap, Uniswap) CarbonMark marketplace for user-friendly credit access Official website and data dashboard Social media and community forums (e.g., Discord, Twitter) Strategic partnerships with external organizations	<b>Customer Segments</b> Corporations and organizations seeking to offset carbon emissions Investors and traders interested in Klima tokens and carbon credits Environmentally conscious individuals supporting climate action DeFi users and the broader crypto community Carbon project developers looking to tokenize and trade their credits
<b>Cost Structure</b> Network and transaction operational costs Ongoing software and platform development Marketing, community engagement, and promotion DAO management and governance coordination Cybersecurity and legal compliance Partnership and collaboration support costs	<b>Revenue Streams</b> Transaction fees from credit trading and retirement Appreciation of Klima tokens held in treasury Revenue from staking and bonding mechanisms Fees for added services (e.g., dashboard, retirement aggregator)	

### 3.3. Allinfra

Allinfra is a Hong Kong-based technology firm at the intersection of climate action, data transparency, and financial innovation. At the core of Allinfra's model lies the ambition to establish tamper-proof environmental datasets that can serve as the backbone for high-integrity environmental assets. This is achieved through the integration of IoT devices,

cloud-based data aggregation, and public blockchain networks. Data collected from sources such as renewable energy installations is first processed and verified, and then immutably recorded on the Polygon blockchain, a scalable Layer 2 solution built on Ethereum. The use of public blockchain infrastructure ensures auditability and traceability, while maintaining scalability and relatively low transaction costs.

Allinfra's system is engineered to support a diverse array of environmental data, including geolocated energy-generation records, timestamps, asset type classifications (e.g., wind, solar), and quantitative outputs. These data streams are not only essential for internal monitoring but are also structured to support external reporting, particularly for the creation of tokenized products like Digital Renewable Energy Certificates and carbon credits. These tokens, which conform to the ERC1155 standard, are created per asset vintage and are non-fungible across vintages, thereby addressing credit fungibility and ensuring rigorous traceability. Once retired, tokens are sent to a burn address, thereby ensuring the finality of claims and preventing the reuse of retired credits. Crucially, Allinfra's use of zero-knowledge proofs enables the platform to publish verified, aggregated data to a public blockchain without disclosing sensitive or commercially proprietary details. This cryptographic innovation enables the company to offer both transparency and confidentiality. Additionally, Allinfra incorporates a dual-verification mechanism in its MRV process: while primary data flows from IoT devices are automatically aggregated and recorded, cross-validation through documentation, such as utility bills and third-party audits, further strengthens the credibility of the records.

Operating without reliance on traditional intermediaries such as certification authorities or brokers, Allinfra aims to streamline the carbon and renewable energy markets through a "trustless" infrastructure. By removing institutional gatekeepers and enabling direct, verified data exchanges between producers and buyers, the company reduces transaction costs, increases accessibility for smaller actors, and enhances market efficiency. Its decentralized data verification and tokenization model not only enhances the credibility of environmental claims but also contributes to democratizing access to carbon markets, an area traditionally dominated by large corporations and specialized intermediaries.

A central theme that emerged from interviews with Allinfra representatives is the platform's strong emphasis on data transparency and reliability in environmental markets. One interviewee stated, *"What we do is we take data from source, usually via IoT-type devices, and then put that climate data onto a blockchain. . . so it's transparent, verifiable, auditable, and, of course, immutable."* This assertion highlights how the platform ensures the integrity of environmental data by leveraging real-time input from IoT systems and recording the information immutably on-chain. Such an approach addresses critical weaknesses in traditional environmental reporting, where data manipulation and unverifiable claims have often compromised credibility. Hashed, aggregated data are stored on the blockchain while detailed data, readings or images are stored off-chain in side databases. This hybrid solution prevails, both for GDPR compliance and data and storage needs.

Another prominent insight relates to Allinfra's robust solution to the problem of double-counting, which remains a major concern in voluntary carbon markets. As one interviewee explained, *"Once the product is retired, it's sent to a burn address, so you can't unburn it and use it again, which can happen in the current traditional market."*

In terms of blockchain governance, Allinfra strongly advocates the use of public blockchains to ensure accountability and transparency. One respondent emphasized, *"We have to use the public blockchain. If it is not in the public chain, it is no different from a centralized database."* However, the company also acknowledges the tension between transparency and data privacy, particularly when dealing with commercially sensitive information. As noted in the interview, *"We aggregate that data before we put it onto the blockchain, and in the aggregation*

process, we also use another technology called zero-knowledge proof.” This solution enables the publication of verified aggregate data on a public ledger while preserving the confidentiality of individual data points. Such an approach demonstrates Allinfra’s commitment to technological innovation that balances transparency with privacy, a critical factor for broader adoption in both corporate and public sectors. A further insight concerns Allinfra’s objective to eliminate intermediaries from the carbon credit lifecycle. The interviewee explained, “The Allinfra platform allows users to create and sell environmental financial products (e.g., carbon credits) with transparent data independently without going through centralised registries like Verra or Gold Standard. On the other hand, buyers can trust the data given the level of transparency.” This disintermediation not only reduces transaction costs and delays but also democratizes access to environmental markets, enabling smaller project developers to participate directly. Lastly, the interview raised important concerns about the lack of economic incentives for individuals to actively engage in carbon offsetting. One participant noted, “Right now, there is limited tangible economic incentive to be net zero. . . it’s more talk than action.” This statement reflects the broader challenge of motivating behavioural change in both individual and organizational settings. Without strong financial drivers, whether in the form of market-based rewards or regulatory penalties, the willingness to participate in voluntary carbon markets may remain limited. This insight points to a critical area for future development, suggesting that for blockchain-based systems to scale impactfully, they must be paired with robust economic mechanisms that drive user engagement.

Table 4 represents Allinfra’s business model within the Business Model Canvas framework.

**Table 4.** Business Model Canvas for Allinfra.

<b>Key Partnerships</b>	<b>Key Activities</b>	<b>Key Resources</b>
IoT hardware providers for accurate and real-time data collection	IoT data collection and integrity verification	Blockchain infrastructure (Polygon network, smart contracts)
Renewable energy partners for source-certified tokens	Blockchain development and maintenance (tokenization, contracts)	IoT network and data aggregation infrastructure
Blockchain ecosystems and scalability providers	Environmental product innovation (carbon credits, dRECTM)	Skilled personnel (developers, environmental analysts, compliance experts)
Regulators and standard-setting bodies for interoperability and legitimacy	Support services for enterprise onboarding and use	Proprietary technologies and intellectual property
Cloud service and cybersecurity partners for infrastructure and compliance	Compliance monitoring and regulatory updates	Strategic alliances with regulators, IoT vendors, and energy producers
Academic institutions for advanced methodological development	R&D for enhanced privacy, data science, and blockchain application	Scalable and secure data storage solutions
<b>Value Propositions</b>		
Transparent, verifiable, and immutable environmental data records through blockchain		
Scalable and efficient MRV process using IoT and blockchain integration		
Tokenization of RECs and carbon credits, directly linked to source data		
Protection of data privacy via aggregation and zero-knowledge proofs		
Elimination of intermediaries, reducing costs and increasing accessibility		
Regulatory compliance support and improved ESG reporting capabilities		
Scalable infrastructure using the Polygon network for high-volume data handling		

Table 4. Cont.

Customer Relationships	Channels	Customer Segments
Consultative onboarding and continuous support for technical integration Transparent data methodologies and access to verified information Educational resources including tutorials and technical documentation Engagement through social platforms, feedback loops, and user communities	Public blockchain (Polygon) for decentralized operations User interfaces, dashboards, and APIs for data access and token management Direct B2B sales, strategic partnerships, and integrations Website, online content, and webinars for awareness and education Presence at sustainability and blockchain industry events	Corporations and organizations aiming to offset carbon emissions and improve ESG reporting Renewable energy producers seeking to tokenize their output through digital certificates Investors and traders interested in digital environmental assets (e.g., dRECTM, carbon credits) Environmental reporting agencies requiring high-quality, immutable data Regulators and governmental bodies involved in environmental compliance and policy IoT device manufacturers seeking partnership in data infrastructure
Cost Structure	Revenue Streams	
Blockchain operational costs (node operation, transactions) Software and platform development IoT hardware procurement and integration Personnel salaries and contractor fees Marketing, partnerships, and client acquisition Legal and regulatory compliance expenses	Fees for tokenization, MRV services, and dashboard access Transaction fees from carbon credit and dRECTM trading and retirement Licencing revenue from proprietary systems and platforms Consulting services for blockchain integration and ESG compliance Monetization of analytics and insights derived from environmental data	

### 3.4. Coorest

Coorest is a Netherlands-based DAO that integrates blockchain technology with real-world tree planting initiatives to create a transparent and verifiable system for carbon compensation. The company aims to build a sustainable digital ecosystem by tokenizing the carbon sequestration process through smart contracts, thereby linking environmental impact directly to blockchain-based financial instruments. Its core innovation lies in the issuance of \$CCO<sub>2</sub> tokens, each representing one kilogram of CO<sub>2</sub> absorbed by living trees, which can be used to compensate for carbon emissions in a secure and traceable manner. Coorest’s mission stems from a critical gap in the sustainability sector, particularly concerning the lack of transparency and verifiability in many carbon-offset projects. As one interviewee explains, “The idea of Coorest was born based on a deficiency that we saw in the market of sustainability, and that was related to the transparency and traceability of data.” By using blockchain technology, Coorest ensures that each token is backed by verifiable carbon-

sequestration data, thereby addressing a major issue in conventional carbon markets where the real impact of funded projects often remains unverifiable. The company's technical infrastructure is built around a three-token model supported by smart contracts. The first token is a non-fungible token (NFT) representing the carbon offset project itself. The second is the \$CCO<sub>2</sub> token, a fungible asset that quantifies the actual amount of carbon sequestered. The third is the Proof of Carbon Compensation, an ERC721 NFT generated when \$CCO<sub>2</sub> tokens are burned. This mechanism ensures that once the carbon has been offset, the associated tokens are permanently removed from circulation, preventing the risk of double counting. As the interviewee describes, *"We do have three different smart contracts with three different tokens, which is the NFT at project level, that is unique. We do have the CO<sub>2</sub> token that is the sequestration of that project. And then we do have something that we call the PoCC."* This represents a significant example to avoid multi-chain duplicate spending. Tokens are sent to a burn address when CO<sub>2</sub> credits are redeemed; they are reinforced by a unique NFT representing the single tree (which is also monitored by IoT devices) and another NFT representing the redeemed CO<sub>2</sub>, making it more difficult to duplicate the same action on multiple blockchain.

A key feature of Coorest's model is NFTrees, digital twins of real trees that serve as generative assets continuously producing \$CCO<sub>2</sub> tokens over time. These digital trees are linked to physical counterparts that are monitored in real time, providing a tangible representation of environmental impact. Users, whether individuals or organizations, can purchase NFTrees and accumulate \$CCO<sub>2</sub> tokens as their trees grow. These tokens can later be burned to generate PoCC certificates or transferred to third parties. This system provides a dynamic user-friendly mechanism for engaging in voluntary carbon offsetting, aligning personal or corporate environmental goals with verifiable outcomes. The MRV process is a cornerstone of Coorest's credibility. The organization uses advanced technologies such as satellite data and Oracles to ensure that the carbon absorption claimed by each NFTree is based on real-world conditions. The interviewee states, *"We verify with satellite data which constantly is passing by the location and provide evidence that a tree hasn't been cut or was not planted or was floating and nobody has done anything."* This level of automated verification drastically reduces the likelihood of fraud or false claims, enhancing the reliability of Coorest's carbon credits. The integration of Chainlink oracles further ensures that off-chain verification data can be securely brought onto the blockchain, thereby closing the gap between digital systems and physical ecological assets.

In terms of governance, Coorest operates under a decentralized model that combines automation with community-driven participation. Smart contracts manage key processes such as token issuance and burning, thereby reducing human error and increasing system efficiency. Blockchain ensures the immutability of transactions, reinforcing stakeholder trust. One of the interviewee's remarks encapsulates this vision: *"For cutting off the middleman, the main thing is that the platform became the middleman."* This statement highlights how Coorest replaces traditional brokers, registries, and third-party verifiers by providing a self-contained, automated infrastructure in which project developers can directly issue, manage, and retire their carbon credits.

A further strength of Coorest's approach lies in its cost model and pricing structure, which aim to democratize access to carbon markets. The price of \$CCO<sub>2</sub> tokens ranges from USD 50 to USD 70 per ton, depending on the purchase volume, while NFTrees are also offered at decreasing rates for larger acquisitions. This flexibility makes carbon offsetting viable for both small-scale users and large organizations, thereby fostering broader participation across market segments. Despite the technological maturity of its system, Coorest acknowledges that adoption remains a significant challenge. As one interviewee notes, *"The adoption of the technology is still very low. We have a finished product,*

but I do not know how long it will take for traditional companies to adopt it, probably three to five years.” While early adoption is primarily driven by the blockchain and crypto communities, participation of larger institutions is essential to establish broader trust and credibility. The interviewee remains optimistic, noting early signs of institutional interest and suggesting that such engagement could catalyze for mainstream adoption.

Table 5 represents Coorest’s business model within the Business Model Canvas framework.

**Table 5.** Business Model Canvas for Coorest.

<p><b>Key Partnerships</b>                  Tree planting projects and landowners                  Blockchain technology providers                  Environmental certifiers and NGOs                  MRV solution providers (e.g., satellite data firms)                  Corporate clients for offset services</p>	<p><b>Key Activities</b>                  Token issuance and management                  Tree planting and carbon absorption tracking                  Platform development and maintenance                  MRV (Monitoring, Reporting, Verification) operations                  Customer support and regulatory compliance</p>	<p><b>Key Resources</b>                  Blockchain infrastructure (Ethereum, smart contracts)                  Real-world forestry assets                  Technical and environmental expertise                  Monitoring and verification systems (satellite, oracles)                  Brand reputation and user community</p>
<p><b>Value Propositions</b>                  Transparent and verifiable carbon offsetting                  Direct link between digital assets and real-world environmental impact                  Competitive pricing for tokens and NFTrees                  Automated processes through smart contracts                  Immutable and secure records via blockchain                  Prevention of double counting and fraud</p>		
<p><b>Customer Relationships</b>                  Personalized support for onboarding and usage                  Community engagement through decentralization                  Transparent records to build user trust                  Long-term corporate partnerships                  Educational content and user guidance</p>	<p><b>Channels</b>                  Coorest’s online platform and dApp                  Direct sales to businesses and institutional clients                  Partnerships with environmental organizations                  Digital outreach (website, social media, content marketing)                  Participation in sustainability and blockchain events</p>	<p><b>Customer Segments</b>                  Companies seeking carbon offsetting for Scopes 1, 2, and 3                  Environmentally conscious individuals                  Investors in sustainable digital assets (e.g., \$CCO<sub>2</sub>, NFTrees)                  Environmental NGOs and organizations                  Blockchain users interested in climate-related applications</p>
<p><b>Cost Structure</b>                  Tree planting and maintenance                  Platform development and operations                  MRV technology and data validation                  Marketing and business development                  Legal and compliance expenses                  Partner commissions and technical support</p>		<p><b>Revenue Streams</b>                  Sale of \$CCO<sub>2</sub> tokens                  Sale of NFTrees                  Transaction and service fees                  Corporate packages and bulk discounts                  Secondary market activity (PoCC and NFTrees)</p>

### 3.5. Hestro

The case of Hestro offers substantial insights into integrating emerging technologies, specifically blockchain and IoT, to foster environmentally sustainable behaviour. Hestro is a technology-driven company based in Italy whose mission is to combine technological innovation with human behavioural change to advance sustainability objectives. The organization focuses on developing IoT platforms that collect, analyze, and certify environmental data, primarily through applications in corporate mobility. Hestro's flagship project centres on an IoT-based system for managing and monitoring e-bike fleets within corporate settings. The platform uses custom-built hardware mounted on e-bikes, to collect real-time data such as kilometres travelled, usage duration, and geolocation. This information is transmitted to a cloud-based platform, enabling companies to track usage patterns, provide services such as insurance or maintenance, and incentivize sustainable commuting habits among employees. In this context, Hestro not only offers a technological product but also positions itself as a behavioural enabler in the corporate sustainability landscape.

To ensure transparency, integrity, and verifiability of the collected data, Hestro employs blockchain technology. The company partners with a Cosmos-based public blockchain network and operates as a validator node, ensuring that data is stored in a decentralized, immutable environment. This infrastructure enables the certification of all environmental data recorded by IoT devices, thereby guaranteeing that the information remains tamper-proof and publicly accessible. The decision to adopt a public rather than a private blockchain reflects a philosophical and technical commitment to decentralization, as highlighted in the interviews. As one interviewee emphatically stated, "A private blockchain is not a blockchain." This perspective aligns with the company's view that public validation is fundamental for establishing trust in environmental claims.

In practice, all collected data is notarized and time-stamped on the blockchain, making it suitable for use in corporate sustainability reports and for compliance with European regulations. This feature is particularly relevant in business-to-business (B2B) applications, where data authenticity must be verifiable by multiple stakeholders. As one interviewee explained, "The data are notarized and stored in a certified environment, nobody can change them, and everybody can access them." This system supports transparency throughout the data lifecycle and facilitates compliance with directives related to carbon emissions and ESG reporting. Although Hestro does not currently employ tokenization in its ecosystem, the company acknowledges its potential, especially in B2C contexts. According to an interviewee, "For the B2C environment, tokenization is a good thing, but in B2B, you have to guarantee stability and not variation of the cost of integration". This pragmatic stance reflects the challenges of implementing blockchain-based tokens in institutional environments, where financial predictability and operational continuity are critical. The integration of IoT and blockchain not only improves the quality and verifiability of sustainability data but also creates indirect incentives for organizations to reduce emissions. For instance, companies that adopt Hestro's system and shift to e-bike-based mobility benefit not only from emissions reductions but also from improved employee health and potential economic advantages, such as access to favourable financing terms tied to ESG performance. In this way, the system aligns environmental impact with business value. Nevertheless, cultural and infrastructural barriers to adoption remain. As observed in the interviews, the broader public and many corporate actors still perceive blockchain as a niche or experimental technology. "Consumers are not using blockchain at all, except for people who train, i.e., people who play the game inside that business", noted one interviewee, highlighting the gap between technical capacity and market readiness. This underscores the importance of education, usability, and regulatory support in fostering mainstream adoption.

Table 6 represents Hestro's business model within the Business Model Canvas framework.

**Table 6.** Business Model Canvas for Hestro.

<b>Key Partnerships</b> E-bike manufacturers and logistics partners Italian public blockchain network (e.g., <i>Commercio.network</i> ) Insurance providers for data-based products AI and tech companies for platform extensions Public institutions for regulatory alignment	<b>Key Activities</b> Development of IoT devices and platform Blockchain data notarization and management Fleet analytics and platform maintenance Customer service and technical training Business development and marketing Research on AI and future integrations	<b>Key Resources</b> Custom IoT hardware and embedded systems Validator role in public blockchain network Cloud infrastructure and secure data management Skilled tech and sustainability team Strategic alliances with mobility partners IP assets and proprietary tech
<b>Value Propositions</b> Blockchain-based certification of mobility data Compliance with EU sustainability directives Real-time IoT fleet management and analytics Reduction of carbon emissions through e-bike use Integration with AI and digital twins Support for employee health and engagement		
<b>Customer Relationships</b> Dedicated account and onboarding support Custom development and integration services Transparent data access and certification Community of sustainability-focused clients Long-term B2B partnerships	<b>Channels</b> Direct corporate outreach and custom sales Partnerships with e-bike manufacturers Online platform and official website Participation in industry events and expos Digital campaigns and social media	<b>Customer Segments</b> Corporations and businesses seeking sustainable mobility solutions Logistics companies for eco-friendly last-mile delivery Municipalities implementing smart and green transportation Fleet managers needing data-driven operations Insurance firms requiring usage-based risk assessment Employees and individual users of corporate e-bikes
<b>Cost Structure</b> R&D for IoT and blockchain innovation Manufacturing of IoT hardware Cloud hosting and blockchain operation costs Salaries and team operations Marketing and customer acquisition Legal and compliance expenses	<b>Revenue Streams</b> Subscriptions to IoT data and services Sales or leasing of IoT hardware Fees for premium analytics and reporting Custom integrations and API access Maintenance and technical support contracts	

### 3.6. StromDAO

StromDAO is a German company pioneering blockchain-based solutions for the energy sector, with a specific focus on enhancing energy efficiency and reducing CO<sub>2</sub> emissions in the residential domain. Through the integration of smart meters and distributed ledger technologies, the company aims to facilitate the transition towards decentralized, data-driven energy systems that empower consumers within evolving electricity markets.

The company's mission is to address Scope 2 CO<sub>2</sub> emissions by providing households and organizations with tools to track and manage their energy use. Unlike many actors operating across diverse energy segments such as gas, heating, or building systems, StromDAO focuses exclusively on the electricity domain, aiming to innovate in both energy consumption and generation management. To this end, StromDAO has developed a comprehensive token-based infrastructure built on Ethereum standards. Its model includes four types of ERC20 tokens: one each for electricity production, electricity consumption, CO<sub>2</sub> emissions, and CO<sub>2</sub> savings. These tokens serve as standardized digital representations of physical energy flows and carbon data, enabling precise, real-time tracking and automated verification. Energy data collected from smart meters is directly recorded on the blockchain, enabling the issuance of tokens based on kilowatt-hours consumed, generated, or saved. This not only enhances system transparency but also facilitates the development of dynamic pricing models and personal carbon accounting. A central element of StromDAO's architecture is the use of smart contracts and a stablecoin to support transactions and peer-to-peer energy trading. The system includes mechanisms to verify proof of origin, ensuring that renewable energy sources are accurately identified and credited. Smart contracts validate data and issue tokens, which can then be traded directly between users or aggregated by service providers. The integration of a stable digital currency enhances usability by allowing participants to trade energy and carbon credits in a familiar, predictable monetary unit.

StromDAO operates on a public Ethereum-based blockchain to ensure decentralization and trust. However, as noted in interviews, the relatively limited number of active validator nodes currently creates a hybrid governance model that balances openness with operational control. This nuanced approach reflects the complexity of implementing blockchain in highly regulated sectors, such as energy. StromDAO GmbH participates as a consortium partner in the BMWK-funded ID-Ideal project (Working Package 8—Energy), where a prototype architecture for fine-grained electricity proofs of origin was developed using Self-Sovereign Identity (SSI) concepts, including Verifiable Credentials (VCs), Decentralized Identifiers (DIDs), and privacy-preserving mechanisms such as shielded NFTs and zero-knowledge proofs. These technologies allow users to retain control over their energy information, authorizing access selectively while maintaining data integrity on chain. The incorporation of validators into the blockchain network further enhances the system's security and reliability. An essential feature of StromDAO's service offering is its robust MRV process. This system combines IoT-enabled smart meters and blockchain infrastructure to automatically monitor energy usage and record associated CO<sub>2</sub> data in real time. The transparency and immutability of this data ensure its credibility, facilitating its use in carbon accounting and energy certification processes. The integration of IoT devices further enhances the granularity and frequency of data collection, strengthening the accuracy and reliability of environmental claims.

Insights from the stakeholder interview emphasize StromDAO's commitment to using blockchain as a verification system. One interviewee explained, *"We actually use blockchain for verification"*, underscoring its role in ensuring the authenticity of electricity usage data. This is made possible by a real-time connection between smart meters and the blockchain, whereby every reading is tracked, stored, and tokenized. The interview further highlighted the multi-token system: *"We have now built a system consisting of four tokens... for electricity production, electricity usage, CO<sub>2</sub> savings, and CO<sub>2</sub> emissions"*, affirming the importance of structuring data for traceability and trading. The discussion also touched on the complexities of blockchain governance. While the system is nominally public, its operational structure today more closely resembles a hybrid blockchain. As the interviewee noted, *"It is a public blockchain, meaning it is not permissioned or restricted in any way. But due to the number of nodes, I would rather call it private or hybrid today."* This distinction is critical

in assessing the practical trade-offs between decentralization and system performance in blockchain-enabled energy applications.

A particularly salient insight concerns the psychological dimensions of energy consumption. The interviewee remarked, *“If you tell people that at certain times energy use is better and at other times worse, you don’t even need to pay them to use the better times... because they feel like they are doing something good.”* This observation underscores the importance of non-monetary incentives, such as information and behavioural nudges, in promoting more efficient energy use without relying solely on financial mechanisms. Nevertheless, barriers remain, particularly in the area of CO<sub>2</sub> pricing. According to the interview, *“Passing on CO<sub>2</sub> pricing to residential users was not possible in this way”*, highlighting the challenges of integrating real-time carbon pricing into household energy bills, despite rising consumer interest in sustainability. Finally, the interview emphasized the potential of SSIs in building user trust and enabling secure, user-controlled data verification: *“We generally work with so-called SSIs”*, the interviewee explained, reinforcing StromDAO’s alignment with emerging principles of data privacy and digital sovereignty.

Table 7 represents StromDAO’s business model within the Business Model Canvas framework.

**Table 7.** Business Model Canvas for StromDAO.

<b>Key Partnerships</b>	<b>Key Activities</b>	<b>Key Resources</b>
Utility providers and grid operators for system integration	Blockchain and platform development with continual upgrades	Ethereum-based blockchain and proprietary smart contracts
Hardware manufacturers supplying smart meters and IoT devices	Smart meter deployment and real-time data integration	Advanced metering infrastructure and IoT devices
Blockchain alliances contributing to shared technological standards	Management of token issuance, trading, and lifecycle	Skilled team in energy markets, blockchain development, and regulatory affairs
Environmental organizations to support mission-aligned initiatives	Execution of robust MRV processes to verify energy and CO <sub>2</sub> data	Strategic alliances with technology and energy stakeholders
Regulatory institutions to maintain alignment with evolving energy policies	Marketing, user onboarding, and client retention strategies	In-depth knowledge of energy compliance standards
<b>Value Propositions</b>		
Real-time and tamper-proof energy data through blockchain-enabled energy tracking		
Decentralized peer-to-peer energy trading fostering green energy consumption		
Dynamic pricing systems that incentivize energy-efficient behaviour		
Self-sovereign identity ensuring user-controlled and secure data management		
Reliable compliance support for regulatory energy reporting		
Enhanced MRV systems ensuring precise and trustworthy CO <sub>2</sub> and energy data		

Table 7. Cont.

<b>Customer Relationships</b>	<b>Channels</b>	<b>Customer Segments</b>
Technical support for device installation and platform onboarding	Web-based and mobile applications for energy tracking and token interaction	Residential users seeking to track and reduce electricity usage and CO <sub>2</sub> emissions
Active user community promoting engagement and behavioural change	Strategic partnerships with utilities to embed StromDAO into existing grids	Small-scale renewable energy producers looking for transparent energy trading platforms
Transparent energy use and emissions communication through the platform	Direct outreach to communities and prosumers for onboarding	Utility providers and grid operators aiming to integrate secure, blockchain-based energy management
Feedback channels to incorporate user insights into development	Participation in energy and blockchain industry events for visibility	Energy traders and aggregators requiring accurate, real-time data for optimized transactions
Long-term partnerships grounded in performance and trust	Digital marketing, including social media, newsletters, and online webinars	Environmental NGOs promoting carbon reduction and decentralized energy models
		IoT and smart meter manufacturers interested in system integration opportunities
<b>Cost Structure</b>	<b>Revenue Streams</b>	
Ongoing platform and software development expenses	Fees from energy token transactions and trades	
Capital investment in IoT and smart meter hardware	Subscription models for premium platform features and analytics	
Operational costs for data infrastructure and blockchain validation	Revenue from data analytics services offered to third parties	
Sales and marketing expenditures for user acquisition	Licencing income from providing blockchain modules to energy firms	
Staffing and administrative costs for support and compliance	Consulting revenue for blockchain energy system integration	

## 4. Discussion

Following an in-depth examination of each case, this chapter presents a comparative analysis of the six case studies, applying the 6C framework.

### 4.1. Cross-Case Comparison

This shift in analytical scale enables movement beyond the idiosyncrasies of individual implementations to uncover broader patterns, contrasts, and underlying dynamics that characterize the ecosystem of blockchain-enabled carbon mitigation. While each case was previously examined for its internal coherence and contextual logic, comparative analysis enables the identification of both convergent themes and divergent pathways in how these initiatives exploit blockchain to address climate-related challenges.

Table 8 below summarizes how each of the six selected blockchain cases aligns with the 6C model.

Table 8. 6C framework.

Case	Context	Construct	Configuration	Cooperation	Capability	Change
CODOS	Urban mobility contexts, supported by local authorities and grants	Mobile app, GPS-based tracking, wallet abstraction, token architecture	Direct interaction with end-users, urban-level pilot partnerships	Municipalities, universities, user communities, mobility operators	Behaviour-based impact quantification, user incentivization, adaptive rewards	Evolving from mobility pilot to broader urban climate engagement platform
KLIMADAO	Global decentralized finance ecosystem with high market volatility	DeFi protocols, carbon offset registries, DAO governance model	Community-based governance, DeFi liquidity layers, registry integration	DAO token holders, liquidity providers, offset registries	Automated carbon retirement, financial instrument programmability	Expanding DeFi use cases, integrating new forms of ecological assets
COOREST	Voluntary carbon markets, intersecting agriculture and digital innovation	NFTrees, satellite monitoring, smart contracts, carbon certification infrastructure	Retail investors and farmers connected via blockchain, project onboarding portal	Landowners, satellite providers, certifiers, retail users	Reliable carbon token issuance, global onboarding infrastructure	Scaling token adoption and standardizing verification processes
ALLINFRA	Corporate ESG frameworks and highly regulated environmental reporting	ESG data platforms, APIs, IoT integration, digital environmental attributes	B2B integration with institutional clients, ESG auditors and asset operators	Corporate clients, sustainability consultants, regulatory bodies	Real-time ESG data delivery, enterprise system compatibility	Integrating with global ESG standards and financial platforms
STROMDAO	European energy market with complex regulatory requirements	Smart meters, decentralized billing systems, energy data infrastructure	Energy cooperatives and prosumers, integrated smart grid model	Energy market regulators, hardware providers, residential users	Automated billing, user-level carbon accounting, smart grid integration	Adapting to regulation and expanding micro-utility network capabilities
Hestro	Experimental local governance environments, public education partnerships	Gamified mobile interface, behavioural tracking modules, educational content	Local communities, schools, and households engaged through gamified challenges	Educators, local NGOs, citizens, and data scientists	Awareness-building, gamified education, personal carbon tracking	From pilot-stage awareness tool to scalable educational ecosystem

The “Context” dimension reveals the diverse institutional, regulatory, and geographical environments in which these initiatives are embedded. Codos and Hestro operate in urban experimental environments, supported by public grants and local authorities. This proximity to civic infrastructure and policy frameworks favours rapid deployment and public engagement but may limit scalability because of reliance on institutional support. In contrast, KlimaDAO operates in the fast-evolving world of DeFi, within a largely self-

regulated, transnational digital environment. This offers speed and freedom to innovate but exposes the initiative to governance risk and reputational fragility. Coorest, bridging agriculture and digital innovation, is embedded in the emerging voluntary carbon market, a context marked by fragmentation, a lack of standardized regulation, and high innovation potential. Allinfra and StromDAO are deeply embedded in tightly regulated sectors: ESG accounting and energy markets, respectively. Their trajectories are shaped by high compliance demands but also benefit from institutional legitimacy and established demand structures. These contextual differences fundamentally condition not only the value propositions but also the capacity of each initiative to form stable and scalable partnerships.

The “Construct” dimension captures the technological and infrastructural foundations that define the initiative’s architecture. Codos and Hestro rely on mobile-first platforms with behavioural tracking modules and gamified UX. KlimaDAO is architected around DeFi protocols and DAOs, creating a system that is native to blockchain logics and operates with minimal institutional intermediation. Coorest builds a unique hybrid architecture that combines satellite monitoring, NFT-based asset representation, and carbon certification infrastructure, illustrating a sophisticated blend of physical and digital constructs [22]. Allinfra integrates APIs, IoT data streams, and ESG reporting tools. StromDAO, meanwhile, embeds blockchain technology in the physical energy grid via smart meters and decentralized billing systems, suggesting a high degree of infrastructural coupling with real-world utilities.

The “Configuration” dimension addresses the pattern of relationships and the architecture of value flows. Codos and Hestro are configured for direct B2C interactions, relying on urban-level pilots and community engagement. Their configuration is horizontal, favouring decentralized, real-time user feedback. KlimaDAO, though decentralized, configures its ecosystem through governance tokens and protocol-managed registries, positioning itself as a meta-layer within the carbon finance value chain. Coorest enables vertical integration between producers (landowners) and investors, creating a blockchain-mediated channel for capital and environmental value to converge. Allinfra pursues a highly institutional configuration: B2B integration with corporate clients, ESG verifiers, and asset managers. StromDAO creates a hybrid configuration: horizontal for energy prosumers and cooperatives, but vertical in its interface with energy market authorities. Each configuration responds to contextual pressures (regulation, decentralization, investment flows) but also shapes how each initiative relates to other actors.

“Cooperation” examines the governance and interaction mechanisms through which each initiative engages its ecosystem partners. Codos and Hestro rely on cooperation with municipalities, universities, and NGOs, highlighting a public-sector-facing ecosystem with shared educational and behavioural goals. KlimaDAO exemplifies token-based coordination, in which governance and collaboration are encoded in smart contracts and managed by DAOs. Coorest works with certifiers, satellite data providers, and retail stakeholders, illustrating a multi-nodal cooperation pattern spanning technical, regulatory, and user domains. Allinfra coordinates with institutional clients and compliance bodies through formal partnerships and data-sharing infrastructure. StromDAO relies on energy market regulators and hardware providers, demonstrating an ecosystem characterized by legal formality and infrastructural coupling. These cooperative structures reflect distinct trust regimes: from informal, community-based trust (as in Codos) to formal institutional trust (Allinfra) to algorithmic trust (KlimaDAO).

Regarding the “Capability” dimension, each initiative has developed distinct core capabilities aligned with its ecosystemic function. Codos and Hestro excel in behavioural engagement, adaptive incentivization, and urban mobility/household carbon tracking. KlimaDAO excels in programmable governance and financial automation, enabling it

to operate at scale within crypto-financial markets. Coorest offers robust mechanisms for tokenized carbon issuance and environmental traceability, grounded in ecological monitoring and digital finance. Allinfra emphasizes data integrity, ESG audit compatibility, and integration with corporate environmental reporting systems, capabilities highly valued in institutional ecosystems. StromDAO enables automated billing, decentralized energy flows, and real-time emissions accounting at the household and grid levels.

Finally, the “Change” dimension highlights each initiative’s evolutionary trajectory within the ecosystem. Codos is transitioning from pilot-scale experimentation to a broader urban climate engagement platform, leveraging partnerships with municipalities and research institutions. This evolution reflects its growing institutional anchoring and the political opportunity structure offered by urban sustainability agendas. KlimaDAO continues to expand by integrating new types of ecological assets and reconfiguring its governance to accommodate more risk-averse and compliance-oriented actors. This trajectory is shaped by the need to gain legitimacy beyond the crypto-native community, in response to market maturation and growing regulatory scrutiny. Coorest is scaling its operations while standardizing its verification protocols to position itself within more formalized carbon accounting regimes. Its path is driven by the fragmentation of voluntary carbon markets and rising demand for credibility and transparency in offset claims. Allinfra is deepening its integration into institutional and financial infrastructures by aligning its data platforms with global ESG standards. This evolution is largely shaped by the consolidation of ESG reporting requirements and the growing role of environmental data in capital markets. StromDAO, embedded in the highly regulated European energy sector, is evolving in response to policy shifts and energy decentralization trends. Its expansion of micro-utility infrastructure reflects both regulatory compliance pressures and growing demand for localized energy autonomy. Hestro, originally conceived as a behaviour-change awareness tool, is developing into a more structured educational ecosystem. Its trajectory is driven by its integration with local public institutions and recognition that long-term impact depends on shifting cultural norms and embedding climate awareness in formal education systems.

These diverse evolutionary pathways are not purely the outcome of internal strategic choice. Rather, they reflect structural couplings between each initiative and its surrounding ecosystem, including regulatory environments, technological infrastructures, institutional alliances, and user expectations. The degree of regulatory constraint, the maturity of the markets involved, and the dominant legitimacy logics in each domain all contribute to shaping how these organizations evolve.

#### 4.2. Clustering the Cases

The comparative application of the 6C framework to the six cases analyzed in this study reveals distinct structural configurations, relational logics, and evolutionary trajectories. Drawing inspiration from Rong et al. (2015), who identified patterns of IoT-based business ecosystems by clustering cases along the six core dimensions of Context, Construct, Configuration, Cooperation [19], Capability, and Change, this research similarly identifies three ecosystem patterns that characterize the blockchain-for-climate domain. These patterns are not rigid taxonomies, but ideal types, i.e., analytical constructs that serve to highlight significant differences in ecosystem architecture, maturity, and openness. Table 9 shows the three patterns of business ecosystem that emerged from the analysis.

**Table 9.** Three patterns of business ecosystem.

<b>6C Dimension</b>	<b>Pattern 1: Civic-User Open Ecosystem (Codos, Hestro)</b>	<b>Pattern 2: Crypto-Financial Open Ecosystem (KlimaDAO, Coorest)</b>	<b>Pattern 3: Institutional Closed Ecosystem (Allinfra, StromDAO)</b>
CONTEXT	Pilot-stage platforms embedded in public sector; civic engagement and urban innovation agenda	Partially regulated, crypto-native or hybrid environments; voluntary market context	Highly regulated environments (ESG, energy); strict compliance and auditing structures
COOPERATION	Co-design with municipalities, NGOs, schools; flexible access for communities and partners	Governance via dao and smart contracts; multi-nodal collaboration with certifiers and data providers	Formal cooperation with corporates, regulators, infrastructure partners; low external openness
CONSTRUCT	Lightweight gamified constructs with open interface, mobile apps, GPS tracking	Blockchain-native constructs with token protocols and environmental asset representation	Robust enterprise systems (IoT, APIs, ESG platforms, smart grid tech); integration-focused
CONFIGURATION	Direct user interaction and feedback loops; flexible and decentralized engagement	Token-based incentive alignment with both retail and institutional actors	Structured, hierarchical configuration; limited user input; technical interoperability
CAPABILITY	Strong behavioural engagement and gamification; learning-oriented; civic incentive models	Financial automation, programmable governance, tokenized ecological assets	System-level data validation, ESG monitoring, billing automation; technical capabilities dominate
CHANGE	From awareness to behavioural shift tools; co-evolution with users and institutions	Expanding scope of tokens and carbon assets; shifts in community governance and standardization	Incremental adaptation to regulation and market standards; formal updates, low user co-creation

The first cluster, defined as the Civic-User Open Ecosystem, includes Codos and Hestro. These initiatives are characterized by early-stage, publicly supported development models that emphasize behavioural engagement, civic participation, and educational outreach, as highlighted in previous studies [23]. Both projects operate in close alignment with municipalities, schools, and NGOs, and function as tools for climate awareness and individual-level change. In terms of context, they are situated in local governance or public grant environments, where experimentation and user-centric innovation are encouraged. Their constructs are lightweight and interaction-driven mobile applications, gamified interfaces, and real-time feedback mechanisms. Cooperation is fluid and participatory, with co-design processes and community engagement at the forefront. These platforms exhibit capabilities centred on incentive design, behaviour tracking, and adaptive user learning, rather than technical robustness or infrastructural depth. Change occurs through incremental co-evolution with user communities and public partners, often shifting from single-purpose pilots to more holistic environmental engagement platforms.

The second cluster, designated the Crypto-Financial Open Ecosystem, comprises KlimaDAO and Coorest. These initiatives operate at the intersection of decentralized finance, environmental tokenization, and digital market infrastructure. Their ecosystems are open in the sense that governance and value flows are managed through tokens, smart contracts, and distributed registries. Both cases exhibit hybrid contextual conditions: while KlimaDAO is rooted in crypto-native, transnational digital environments, Coorest engages with physical landowners and agricultural processes through blockchain mediation. The

constructs are technically complex, built around programmable finance and tokenized environmental assets. Cooperation takes place through decentralized governance (as in KlimaDAO) or via digitally mediated marketplaces (as in Coorest), often involving certifiers, data providers, and platform users in loosely coupled arrangements. These platforms excel in capabilities such as financial automation, ecological asset standardization, and scalable onboarding mechanisms. Their evolutionary dynamics are defined by expansion and integration, broadening the range of tokenized resources, refining market standards, and incorporating institutional partners over time.

The third cluster, identified as the Institutional Closed Ecosystem, includes Allinfra and StromDAO. These platforms are embedded in highly regulated sectors and are structurally closed in their operational and governance logics. Unlike the previous clusters, these initiatives do not rely on broad public engagement or open participation, but instead pursue formal integration with established institutions, regulatory frameworks, and infrastructural systems. Their context is shaped by compliance demands and legacy system constraints. The construct in both cases is enterprise-grade: Allinfra leverages APIs, IoT sensors, and ESG data services for B2B clients, while StromDAO builds blockchain solutions embedded in smart grid technologies and billing architectures. Cooperation is formalized, hierarchical, and often long-term, involving contracts with regulators, utilities, and corporate actors. Their capabilities are oriented toward data auditability, reliability, and interoperability, rather than experimentation or adaptability. Change in this pattern tends to be incremental and compliance-driven, with transformation driven by updates to standards, regulations, or partner requirements rather than by user innovation or token evolution.

#### *4.3. Mapping Organizational Logics: Insights from Gioia Coding*

To further deepen the analytical lens and move beyond surface-level comparisons, the analysis adopted a structured inductive framework to identify underlying patterns across the six cases. This next phase of the study employs the Gioia methodology, a well-established qualitative approach for concept development that emphasizes the systematic construction of data structures from rich empirical material. The method is particularly suited for research domains characterized by high novelty, complexity, and interpretive richness, such as the emergent intersection of blockchain technologies and climate governance. Unlike traditional thematic coding, which often stops at descriptive categories, the Gioia method involves progressive abstraction of data, proceeding from the language of informants (first-order concepts) to researcher-centric interpretations (second-order themes) and ultimately to theoretically meaningful aggregate dimensions. This structure facilitates both analytic clarity and theoretical depth, enabling a transparent trace from empirical evidence to conceptual insight.

To integrate the Gioia data structure with the analytical narrative, the study explicitly links the inductively derived dimensions to the 6C framework. The Gioia method provides the empirical foundation for the analysis, and the resulting aggregate dimensions are interpreted through the 6C lens to explain how blockchain-based initiatives operate in terms of Context, Construct, Configuration, Cooperation, Capability, and Change. For instance, the aggregate dimension Emerging technologies for climate transparency is derived from themes on technological reliability, auditability, and user-centric design and is primarily analyzed as a Capability and Construct, capturing the technical capacity and data logic that enable verifiable climate claims, while secondarily influencing system Configuration. The distinction between strong and weak arrows in the data structure reflects this analytical hierarchy: strong links indicate dimensions that directly generate transparency outcomes through core technical capabilities, whereas weak links denote supporting dimensions that shape accessibility, coordination, or ecosystem arrangements without independently

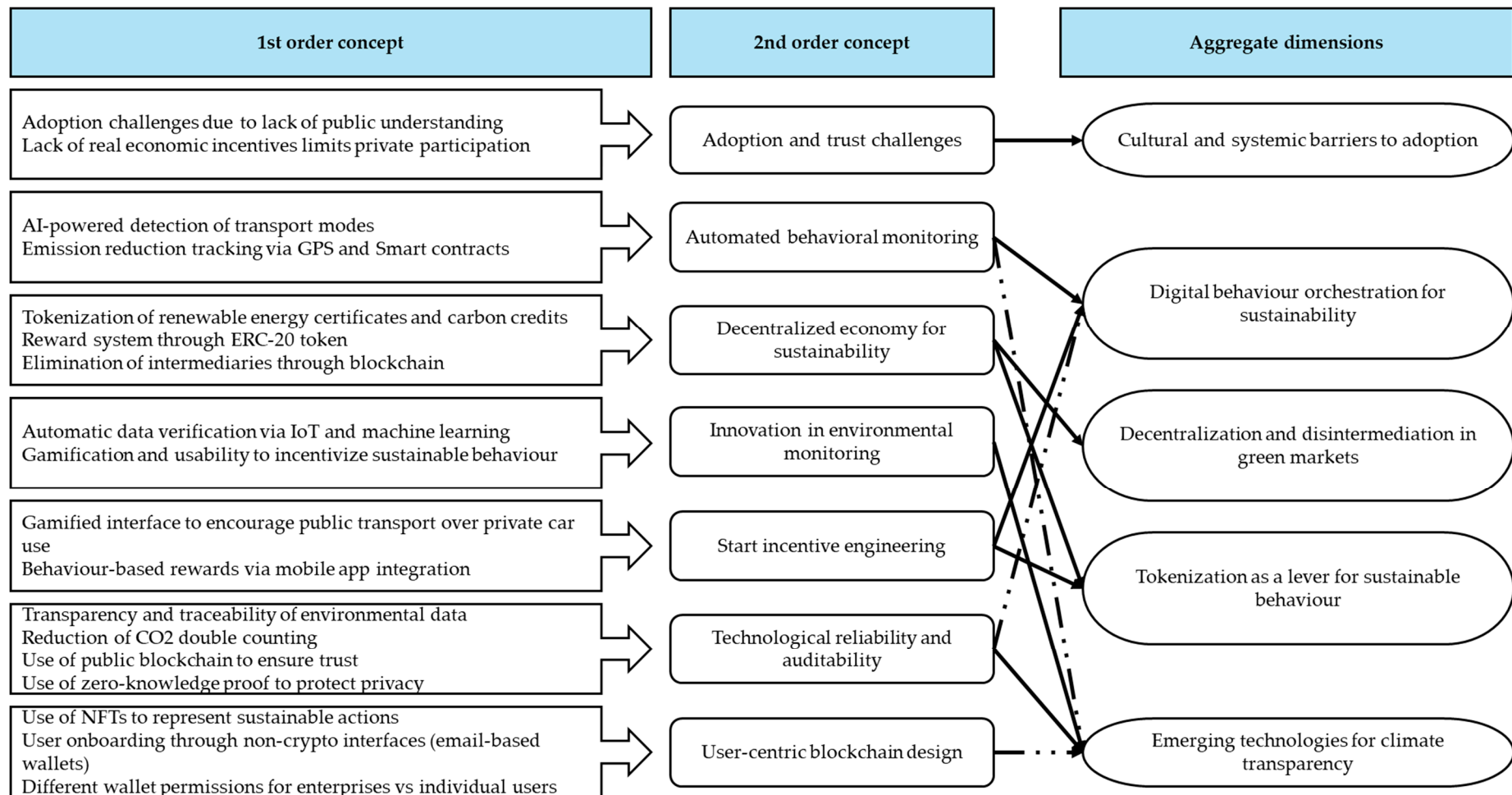
ensuring claim integrity. Through this process, subtle yet significant cross-case regularities become visible, offering insights into how these initiatives, despite their diverse operational logics, collectively navigate similar challenges in aligning digital infrastructures with environmental goals. This is not merely a classificatory exercise; instead, it provides a conceptual scaffolding for understanding how blockchain is being enacted as an instrument of climate action across varied institutional, technical, and social contexts. The resulting data structure, presented in Figure 1, summarizes this interpretive synthesis.

Figure 1 represents the structured outcome of the inductive analysis conducted using the Gioia methodology. It visually maps the progression from empirical observations to conceptual abstraction, offering a transparent, systematic framework for interpreting how blockchain-enabled climate initiatives are internally configured.

The first-order concepts derive directly from the empirical material gathered across the six case studies. They remain close to the language and framing used by the actors themselves, whether in interviews, documents, or public communications. These include practical implementations such as “AI-powered detection of transport modes,” “tokenization of carbon credits,” or “gamified interface to encourage public transport use,” as well as perceived obstacles such as “lack of public understanding” or “limited presence of economic incentives.”

Through iterative coding and abstraction, these granular insights are grouped into second-order themes. These themes represent interpretive categories developed by the researcher to capture recurring patterns that transcend individual cases. For example, the challenges of user disengagement and the absence of clear financial rewards are synthesized into the theme “adoption and trust challenges.” Similarly, various forms of technological automation designed to monitor energy-saving behaviours or mobility choices are grouped under “automated behavioural monitoring.” These themes are not arbitrary labels but reflect deliberate interpretive moves, grounded in the repetition and coherence of empirical patterns across diverse contexts.

The aggregate dimensions capture the broader, cross-cutting logics that shape how blockchain is mobilized as a climate tool. These dimensions describe how organizations orchestrate technological, behavioural, and institutional elements to pursue environmental outcomes. For instance, the theme “user-centric blockchain design” is associated with the dimension “digital behaviour orchestration for sustainability,” signalling that design decisions are not merely technical conveniences but mechanisms for influencing user engagement and behavioural alignment. At the same time, the same theme is connected, albeit more weakly, to “emerging technologies for climate transparency,” acknowledging that even interface design may contribute indirectly to broader systems of accountability and traceability.



**Figure 1.** Aggregated dimensions findings under the Gioia methodology. Solid arrows denote strong, direct conceptual relationships between themes and dimensions, with empirical evidence consistently supporting a coherent, robust linkage. Dashed arrows, by contrast, represent weaker or more indirect associations.

This duality of connections is made explicit in the visual diagram. Solid arrows denote strong, direct conceptual relationships between themes and dimensions, with empirical evidence consistently supporting a coherent, robust linkage. Dashed arrows, by contrast, represent weaker or more indirect associations. These weaker connections are not analytically marginal; instead, they reflect secondary roles or overlapping functions that specific themes perform across conceptual domains. For example, “technological reliability and auditability” is primarily understood as a function of transparency infrastructure, but also supports behavioural orchestration by underpinning user trust in system outputs. Similarly, “smart incentive engineering” closely relates to behavioural orchestration and also anchors the logic of “tokenization as a lever for sustainable behaviour,” indicating how technical reward mechanisms serve as both motivational tools and vehicles for environmental value creation. The structure also reveals non-trivial patterns in the distribution of strategic emphasis across initiatives. Some dimensions, such as “digital behaviour orchestration for sustainability,” aggregate a broad range of themes, suggesting a more integrative or cross-functional strategic logic. Others, like “decentralization and disintermediation in green markets,” are more narrowly connected, indicating a more focused, domain-specific application. What emerges is not a uniform conceptual field but a differentiated landscape in which themes serve multiple roles and in which aggregate dimensions vary in the density and strength of their supporting evidence.

By tracing how concrete practices are progressively abstracted into broader conceptual categories, this data structure does more than organize findings: it crystallizes the underlying architecture of how blockchain technologies are being translated into climate interventions.

#### *4.4. Discussion of Research Questions*

Drawing on a multi-level analytical approach that integrates case-based evidence and the structural perspective of the 6C Framework, the discussion reveals distinct patterns of organizational logic, technological design, and systemic positioning. At the core of the analysis is the understanding that blockchain does not operate in isolation but rather as part of broader socio-technical ecosystems, in which contextual conditions, actor configurations, and strategic capabilities shape its effectiveness and transformative potential. To address RQ1, the empirical material shows that blockchain contributes to this objective through three interrelated mechanisms: incentivizing behavioural change, enabling decentralized control over energy flows, and creating auditable data infrastructures that support energy accountability. These mechanisms manifest differently across cases. In Codos and Hestro, blockchain is primarily used as a behavioural orchestration layer, rewarding sustainable commuting or household practices through gamified interfaces and token-based incentives. StromDAO, in contrast, embeds blockchain into smart grid infrastructure, using it to automate micro-utility billing and track real-time energy flows. While Codos and Hestro emphasize behavioural interventions, StromDAO focuses on infrastructural transparency. Hence, blockchain reduces residential energy consumption not solely through technical automation, but by aligning user behaviour, digital incentives, and verifiable data within a structured ecosystem.

These differences lead directly to the second research question, RQ1a. The analysis identifies two viable models. The first is a user-centric, participatory model that pairs lightweight technological constructs (apps, wallets, smart contracts) with civic partnerships and behavioural incentive mechanisms. This model, exemplified by Codos and Hestro, is coherent as far as its technological simplicity is matched by strong social embedding and flexible institutional cooperation. The second model, illustrated by StromDAO and Allinfra, is grounded in deep infrastructural integration. These systems rely on high

regulatory alignment and enterprise-grade architectures that prioritize accuracy, stability, and compliance. What makes each model coherent is not its structure per se, but the consistency between ecosystem position, governance logic, and stakeholder alignment [24]. In Civic-User ecosystems, coherence is derived from openness and community anchoring; in Institutional ecosystems, coherence is derived from technical rigour and regulatory fit.

Regarding RQ1b, the study finds that effectiveness does not hinge on the public or private nature of the blockchain or on the use of any specific protocol, but rather on the modular integration of the blockchain with context-specific technologies. For behaviourally driven systems like Codos, effectiveness stems from coupling smart contracts with geolocation and mobile UX design, ensuring that sustainability incentives are both meaningful and verifiable. In infrastructure-intensive systems like StromDAO, the key lies in interfacing the blockchain with IoT-enabled smart meters and local energy cooperatives. The 6C dimensions of Construct and Capability illuminate this distinction, showing that effective technological choices enable granular data traceability, interoperability, and actionable feedback loops within the user or energy system.

Finally, RQ2 is addressed through a comparative study of MRV practices across all six cases. The research finds that the limitations of the carbon market (i.e., lack of transparency, double counting, unverifiable claims) are mitigated by hybrid strategies that blend technical automation with institutional embedding. KlimaDAO and Coorest, operating within the Crypto-Financial Open Ecosystem, leverage blockchain to enable decentralized MRV through tokenized assets, satellite imagery, and innovative contract execution. Yet both also depend on auxiliary mechanisms to stabilize trust and build market credibility. Allinfra, within the Institutional Closed Ecosystem, complements its blockchain layer with ESG-compatible reporting infrastructure, ensuring financial and regulatory bodies accept its data outputs. What emerges is that MRV systems are most robust when they combine algorithmic integrity with institutional legitimacy, embedding data generation and verification within externally accountable, decentralized workflows.

Across all three ecosystem patterns, change trajectories reflect not only internal growth dynamics but also ecosystem-induced adaptation. Codos and Hestro scale through deeper civic embedding and education; KlimaDAO and Coorest evolve by diversifying token functions and onboarding new asset types; Allinfra and StromDAO adapt incrementally to regulation and infrastructural shifts. These change processes confirm that the evolution of blockchain-enabled sustainability systems is relational and path-dependent, shaped as much by external pressures and actor constellations as by technological capabilities or internal strategy.

## 5. Conclusions

The findings of this research shed light on the complex ways in which blockchain technologies are being mobilized to address environmental challenges, particularly in reducing residential energy consumption and restructuring carbon measurement and verification systems. Drawing on a multi-level analytical approach that integrates case-based evidence and the structural perspective of the 6C framework, the analysis reveals distinct patterns of organizational logic, technological design, and systemic positioning. At the core of the results is the understanding that blockchain does not operate in isolation but rather as part of broader socio-technical ecosystems, in which contextual conditions, actor configurations, and strategic capabilities shape its effectiveness and transformative potential.

### 5.1. Theoretical Implications

The findings of this study offer several contributions to the theoretical understanding of how blockchain technologies are embedded within emerging sustainability ecosystems, bridging micro-level concept emergence with meso-level systemic structures.

First, this study shows that blockchain functions as a socio-technical infrastructure whose role is mediated by context, organizational logic, and ecosystem configuration. In particular, the same core technology enables radically different outcomes depending on how it is orchestrated. This insight complements and extends existing work in the sustainability transitions literature [25] by showing that digital innovations do not act as monolithic transition engines, but instead evolve through contingent alignments among actors, infrastructures, and regulatory signals.

Second, the identification of three ecosystem patterns contributes to the literature on digital platform ecosystems [26]. These patterns reveal that platform architecture and ecosystem openness are not binary attributes but exist on a spectrum conditioned by institutional embeddedness, technological constructs, and value logics.

Third, the study extends resource orchestration theory to blockchain-enabled sustainability platforms. Each case mobilizes a distinct combination of technical, relational, and institutional resources. Civic-User platforms emphasize user engagement and public trust. Crypto-Financial initiatives orchestrate liquidity, standardization, and credibility through token mechanisms. Institutional platforms build capabilities around compliance, traceability, and operational stability. These differences support the proposition that dominant value logics shape how capabilities are bundled and leveraged, influencing platform trajectories.

Finally, the study enriches research on MRV systems in carbon markets. By showing how blockchain platforms integrate automated monitoring with institutional validators, it highlights the emergence of hybrid MRV architectures that combine decentralization (transparency, auditability, immutability) with institutional credibility, offering a pathway to address opacity, fragmentation, and high transaction costs.

### 5.2. Managerial and Policy Implications

The findings offer relevant implications for managers and policymakers seeking to deploy blockchain technologies in support of climate objectives, particularly for residential energy efficiency and carbon markets. By identifying distinct ecosystem configurations, the study underscores the importance of context-specific strategies rather than generic technological approaches, and highlights how organizational, technological, and verification choices shape platform credibility and effectiveness.

For platform developers and managers, the results show that technological design and governance must align with ecosystem position. Civic-oriented platforms such as Codos and Hestro benefit from simple designs, behavioural incentives, and institutional partnerships. Their success depends more on trust, participation, and local legitimacy than on cryptographic sophistication. In contrast, platforms like Allinfra and StromDAO, operating in regulated domains, must prioritize compliance, data reliability, and interoperability. For these actors, blockchain primarily functions as an infrastructure layer within enterprise or public systems, where the managerial priority is secure, auditable, and policy-aligned data flows. Crypto-Financial ecosystems such as KlimaDAO and Coorest operate in more fluid environments, where maintaining credibility requires balanced governance, verifiable data sources, and partnerships with external validators.

From a policy perspective, these differences call for differentiated regulatory approaches. Civic platforms may benefit from sandbox environments and public data access; crypto-financial platforms require standards and oversight for tokenized environmental assets; infrastructure-linked platforms call for legal frameworks recognizing blockchain-

based audit trails in energy and ESG systems. Across all models, policymakers can use these insights to support innovation while safeguarding transparency and public trust.

### 5.3. Limitations and Future Research

As with any qualitative inquiry grounded in interpretive methodology, this study has certain limitations that define its analytical scope.

First, the comparative multiple-case design, based on six initiatives, limits the generalizability of the findings. The cases are skewed toward Western, early-stage projects with experimental governance structures. Future research could include more geographically diverse cases, particularly from contexts where blockchain is applied under different institutional conditions.

Second, the analysis relies on qualitative data interpreted through the Gioia methodology and the 6C framework. While suitable for capturing emergent concepts and ecosystem patterns, this approach does not test relationships or measure outcomes. Future studies could adopt quantitative, longitudinal, or experimental designs to assess the actual impact of blockchain platforms on energy consumption, emissions reduction, and user behaviour.

Third, the ecosystem patterns identified are ideal types that simplify real-world complexity. Platforms may evolve across archetypes or display hybrid configurations. Future research could adopt established theoretical lenses, such as Socio-Technical Transitions Theory or Institutional Theory, and examine how ecosystem configurations evolve over time, including cross-ecosystem interactions and regulatory experimentation.

Overall, the study suggests that blockchain's contribution to climate action depends primarily on the ecosystem in which it is embedded. Its role and potential are shaped less by technological features than by governance models, institutional arrangements, and stakeholder participation. Effective implementation therefore requires ecosystem-sensitive strategies that align technological design, incentives, and regulation with contextual conditions.

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## Abbreviations

The following abbreviations are used in this manuscript:

B2B	Business-to-business
B2C	Business-to-consumer
DAO	Decentralized autonomous organizations
DeFi	Decentralized finance
MRV	Measurement, reporting and verification
NFT	Non-fungible token
RQ	Research question

## Appendix A. Interview Guide

### Organizational Structure and Project Integration

1. Can you provide an overview of the project you are currently working on?
2. Could you describe the key roles within your organization and how they contribute to the project's success?
3. How is decision-making structured within your organization? Who is responsible for setting the rules and guidelines within your organization, particularly in relation to the project?
4. What is the overarching purpose or mission of your organization, and how does the current project align with that mission?

### Blockchain Evaluation and Governance System:

1. How is blockchain technology specifically utilized within your organization?
2. Can you provide insights into the key applications? What aspects or processes are managed using blockchain within your organization?
3. Which blockchain do you operate, and how would you assess its user-friendliness and performance?
4. In your experience, what are the primary benefits that blockchain brings to your organization? Additionally, have you encountered any challenges in implementing or utilizing blockchain effectively?
5. In blockchain governance, access rights vary across different models. Public blockchains provide open-access to all, with decentralized governance. Private blockchains restrict access to selected participants, emphasizing centralized control. Consortium blockchains, a middle ground, involve collaborative governance among multiple organizations, allowing shared access rights and balanced control.
6. Additionally, which governance system—private, public, or consortium—do you currently employ, and what factors influenced your choice? And how do these privileges differ between interacting with the blockchain and using applications?
7. In blockchain governance, it is important to note that access rights can differ not only at the blockchain level but also at the application level. This means users may have different permissions depending on whether they are interacting with the blockchain itself or with specific applications built on top of it.
8. Specifically, how do you manage to verify the data on the blockchain, and which consensus model do you employ for this purpose?

9. Furthermore, how do you establish the connection between real values and tokens, such as through smart contracts or NFTs?

Reward System and Token Usage:

1. How do you currently reward users, and do you utilize a token (utility or payment)?
2. Can you give an insight into the possibilities available to users with the token and the token creation process?

Measurement, control, verification, and privacy:

1. In measuring the reduction in energy and associated CO<sub>2</sub> avoidance, which methods do you employ to ensure accurate measurements without compromising the privacy of users?
2. Given the increased behavioural risks for residential users, such as fraud, double-counting, and the rebound effect, how do you propose to overcome these obstacles?
3. In view of the importance of compliance, could you explain the methods and controls required to ensure reliable data collection?

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