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Cybernetic Environmental Hubs for Just Energy Transition: A Viable System Model Framework for Governance in the Global South

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Abstract

Just energy transitions in the Global South unfold under conditions of institutional fragmentation, fiscal constraints, and high socio-ecological turbulence, making governance capacity a critical bottleneck for effective decarbonization and climate justice. This study proposes the Cybernetic Environmental Hub (CEH) framework, which extends the Viable System Model (VSM) to sustainability governance by integrating AIoT-enabled environmental monitoring, Early Warning Systems, decentralized data governance, and justice-centered institutional design. Methodologically, the article is primarily a conceptual framework paper accompanied by an illustrative single-site qualitative case study designed to probe the plausibility and diagnostic utility of the proposed architecture rather than to generate statistical generalization. The research combines theoretical development with participatory territorial diagnostics in the Caribbean Mining Corridor, where socio-ecological challenges were collected through participatory innovation workshops, thematically coded, and mapped onto the five VSM subsystems to identify systemic "variety gaps." The analysis indicates that fragmented operational initiatives coexist with weak meta-systemic coordination, limiting adaptive capacity in energy transition processes. The CEH architecture is proposed to address these deficiencies by embedding AIoT sensing, federated learning, blockchain-based coordination, and Early Warning Systems within recursive governance structures and is grounded in a real cyber-physical deployment of around 90 monitoring stations across Albania, La Jagua de Ibirico and Algarrobo. The study also introduces a Territorial Governance Maturity Model (H1–H3) to diagnose systemic learning capacities and transition readiness across technological, institutional, data governance, and justice dimensions. The findings suggest that cybernetic environmental hubs may function as socio-technical infrastructures supporting coordinated, adaptive, and justice-centered energy transitions in the Global South, while comparative empirical evidence remains an agenda for future work.

Keywords: Cybernetic Environmental Hubs; Viable System Model (VSM); Just Energy Transition; AIoT Environmental Monitoring; Early Warning Systems; Climate Justice Governance; Open Environmental Data Governance; Global South

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1. Introduction: Governing Just Energy Transitions in the Global South

Just energy transitions (JETs) in the Global South are not merely technology substitution processes; they are structural transformations unfolding under conditions of severe fiscal constraint, deep socio-economic inequality, and acute climate vulnerability [1,2]. In such contexts, the dominant bottleneck is increasingly governance capacity—the ability of institutions and multi-actor coalitions to coordinate across fragmented mandates and territorial scales [3,4]. Consequently, the literature converges on the urgent need for systemic architectures capable of steering these transitions while absorbing the high levels of environmental and social complexity inherent to emerging regions [5].

Figure 1 illustrates the systemic governance challenges that characterize energy transitions in the Global South.

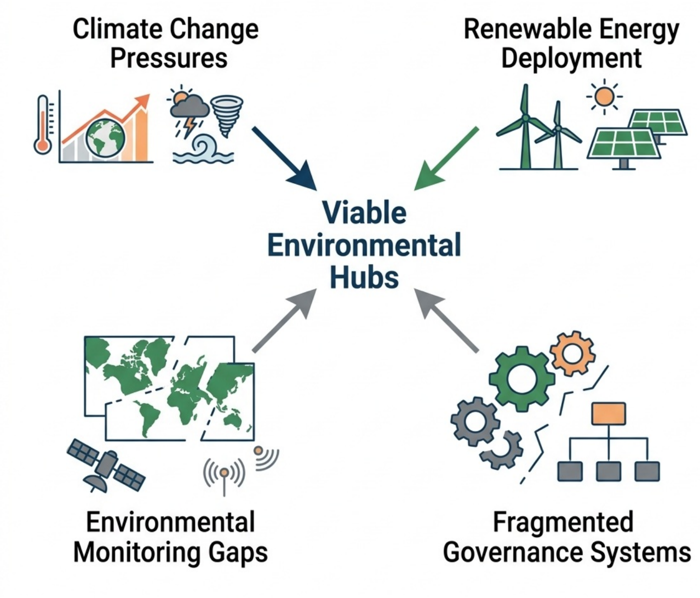

Figure 1. Systemic governance challenges in just energy transitions in the Global South.

The justice dimension of these transitions is a central, non-negotiable concern. Traditional governance approaches often treat climate justice as an ex post compensatory mechanism rather than a foundational structural design condition [6]. Recent critiques emphasize that without profound structural redesign, transitions risk reproducing extractive patterns of dependency and neo-colonial resource exploitation [7,8]. True just energy transitions, therefore, demand governance models that embed equity, procedural inclusion, and social protection directly into their operational and decision-making architecture [9].

Despite these imperatives, existing governance models frequently exhibit significant structural limitations. Contemporary approaches, such as polycentric and network governance, offer valuable descriptive lenses but often fail to provide normative guidance for institutional redesign under high socio-ecological complexity [10]. Furthermore, they tend to lack the necessary mechanisms for integrating continuous socio-technical feedback loops and resolving cross-level coordination conflicts [11,12]. Thus, there remains an unaddressed need for architectures that successfully balance local autonomy with overarching systemic cohesion [13].

This theoretical fragmentation is compounded by a technological silo effect. Advanced digital tools, such as Artificial Intelligence of Things (AIoT), Early Warning Systems (EWSs), and digital twins, are frequently deployed as isolated engineering solutions, disconnected from the very institutional decision-making structures they are meant to inform [14]. At the same time, high-profile multi-level financing mechanisms like Just Energy Transition Partnerships (JETPs) suffer from coordination overload and prohibitive transaction costs [15,16]. Without transparent, decentralized open environmental data governance—supported by technologies like federated learning and blockchain—distributed sensing does not translate into distributed governance capacity [17,18]. The structural research gap is clear: the literature provides the theoretical and technological components (governance frameworks, cybernetic principles, AIoT sensing, and justice ideals) but lacks a unified, operational design to integrate them.

In terms of methodological identity, this article is best read as a *conceptual framework paper* whose argument is illustrated and refined through a single-site qualitative case study, rather than as a mixed-methods empirical paper. The empirical anchor is the Caribbean Mining Corridor (Albania, La Guajira; La Jagua de Ibirico, Cesar; and Algarrobo, Magdalena), a territory affected by open-pit coal mining, methane and particulate emissions, water-stress conflicts between extractive and agricultural uses, and documented public-health vulnerabilities (respiratory disease in exposed populations). It is also a setting in which Colombian climate-justice jurisprudence has begun to crystallize, e.g., Constitutional Court ruling T-614/2019, the air-quality Resolución 2254/2017, and ANLA-led environmental compliance procedures. These conditions provide a real, verifiable governance test bed for the Cybernetic Environmental Hub (CEH) framework. This article makes four main contributions to the literature on sustainability governance and energy transitions. First, it introduces the concept of *Cybernetic Environmental Hubs*, conceptualized as socio-technical infrastructures for coordinating environmental monitoring, data governance, and energy transition processes. Second, it extends the *Viable System Model* (VSM) to the field of sustainability governance by operationalizing recursive environmental governance across territorial scales. Third, it develops a diagnostic analytical framework that maps territorial governance challenges into VSM subsystems and proposes a territorial governance maturity model. Fourth, it provides policy-relevant insights by demonstrating how environmental hubs can support institutional coordination and adaptive governance in energy transition processes.

To achieve this, the study is guided by three interrelated research questions (RQs) and associated propositions (Ps):

- **RQ1:** How can the Viable System Model (VSM) enhance governance coordination in regional energy transitions?
  P1: Cybernetic structuring enhances institutional coherence. Institutional behavior is shaped by structural architecture. By deploying VSM-based mechanisms, institutions can balance operational autonomy with systemic cohesion, mitigating fragmentation while aligning multiple institutional and community actors toward shared decarbonization and justice objectives [10].
- **RQ2:** How can AIoT and Early Warning Systems be structurally embedded in governance systems?
  P2: AIoT integration increases adaptive capacity. Embedding digital infrastructures—AIoT sensors, blockchain, and federated learning—within the intelligence (System 4) and coordination layers of governance amplifies predictive foresight and real-time response, allowing systems to manage complexity securely and transparently [19,20].
- **RQ3:** How can territorial maturity be assessed systemically?
  P3: Territorial maturity is path-dependent and systemically emergent. A territory's capacity to execute just transitions is not externally installable; it emerges from historical, recursive institutional learning. Maturity evolves as territories move from operational reactivity to deep cybernetic reflexivity [12,21].

Through this hybrid conceptual–empirical design, the article positions organizational cybernetics as a candidate institutional engineering framework for operationalizing justice and viability. To avoid ambiguity about its epistemic status, this manuscript is primarily a conceptual framework paper accompanied by an illustrative qualitative case study intended to probe the plausibility, internal coherence, and diagnostic utility of the proposed architecture. It is not a mixed-methods empirical paper, and the single-site application in the Caribbean Mining Corridor is used for framework validation and refinement, not for statistical generalization. Comparative and quantitative testing across additional territories is explicitly identified as a priority agenda for future work and is discussed in Sections 11 and 12.

The analytical structure of the article is summarized in Figure 2.

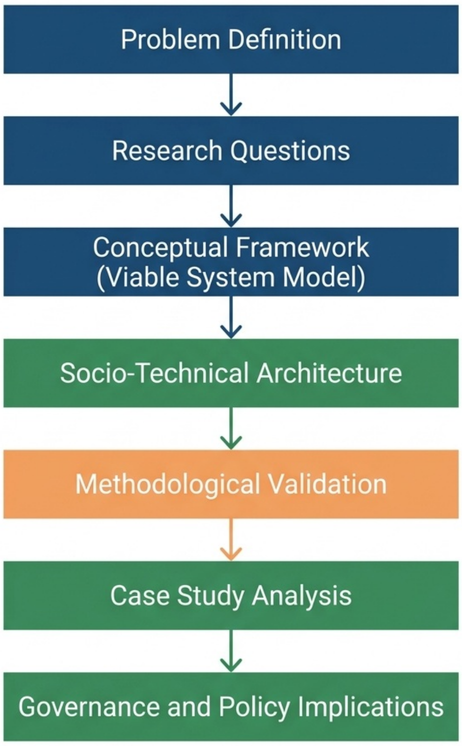

Figure 2. Analytical structure of the article.

2. Literature Review and Theoretical Positioning

2.1. The Viable System Model and Cybernetic Governance

Organizational Cybernetics provides the theoretical foundation for maintaining systemic viability under extreme complexity. Beer (1981) establishes the Viable System Model (VSM) as a formal framework derived from neurophysiology, defining the necessary and sufficient structural conditions for an organization to maintain an independent existence within a dynamic environment [22]. Subsequent studies have expanded this perspective, demonstrating how the VSM's five interacting subsystems—operations, coordination, control, intelligence, and identity—function cohesively to absorb internal and external perturbations [23,24]. Therefore, the literature converges on the premise that the VSM offers a mathematically grounded architecture for diagnosing and designing resilient institutional structures [25].

The core regulatory mechanism underpinning the VSM is the Law of Requisite Variety. Ashby (1956) establishes that "only variety can absorb variety," meaning a governance system must possess internal complexity equal to or greater than the environmental turbulence it attempts to manage [26]. Other authors have expanded this principle to socio-ecological systems, showing that rigid, hierarchical command-and-control frameworks systematically fail because their internal variety is insufficient to match rapidly changing climate and social dynamics [27,28]. Consequently, maintaining systemic viability requires decentralized architectures that maximize operational autonomy while enabling continuous structural adaptation [29].

Recent applications of the VSM have transitioned from corporate management toward sustainability and common-pool resource governance. Espinosa (2022) establishes the framework's relevance for empowering self-governing communities to manage complex socio-ecological transitions from the bottom up [30]. Empirical studies corroborate this by demonstrating that cybernetic principles provide the structural scaffolding necessary for sustainable organizational renewal and effective resource optimization under severe ecological constraints [21,31]. Therefore, the VSM provides not only a descriptive lens but an emancipatory and normative design methodology for grassroots sustainability initiatives [32].

A fundamental strength of the VSM is its recursive, fractal logic for multi-level governance. Espinosa and Duque (2018) note that every viable system contains and is contained within other viable systems, allowing the exact same functional architecture to operate from local indigenous cooperatives to national policy platforms [33]. This recursive design enables precise multiscale diagnostics and clear interface definitions, preventing the center–periphery power imbalances common in traditional planning [28,34]. Thus, recursive cybernetic structuring balances necessary local operational autonomy with indispensable meta-systemic cohesion, making it an optimal blueprint for large-scale climate interventions [10].

2.2. Complexity Governance and Framework Comparison

Despite the robustness of cybernetic principles, contemporary environmental governance often relies on parallel theoretical approaches that describe complexity but struggle to structurally manage it. Ison et al. (2014) established that adaptive governance enhances resilience through iterative learning-by-doing, yet it often lacks a formalized multi-level institutional design capacity [11]. Transition Management and Polycentric Governance similarly highlight the importance of niche innovation and distributed decision-making, though they frequently face high transaction costs or technocratic biases that obscure socio-political trade-offs [12]. Consequently, to operationalize these descriptive insights, a cybernetic synthesis is required to guarantee structural coordination, continuous feedback, and adaptive intelligence across governance layers [13].

Figure 3 compares the main governance frameworks discussed in the literature and highlights the analytical gap addressed by this study.

2.3. Just Energy Transition Governance

In the Global South, the imperative for robust governance architecture is magnified by the financial, political, and historical complexities of energy transitions. The Presidential Climate Commission (2022) established the Just Energy Transition Investment Plan (JET-IP) framework, emphasizing that systemic shifts require more than technological substitution; they demand comprehensive socio-economic redesign and restorative justice [16]. Similar mechanisms deployed internationally reveal that coordinating multiple domestic, international, and financial actors generates massive administrative friction and coordination overload [35,36]. Thus, the literature converges on the reality that without a cohesive multi-level architecture, transition partnerships risk becoming fragmented mechanisms rather than transformative ecosystems [37].

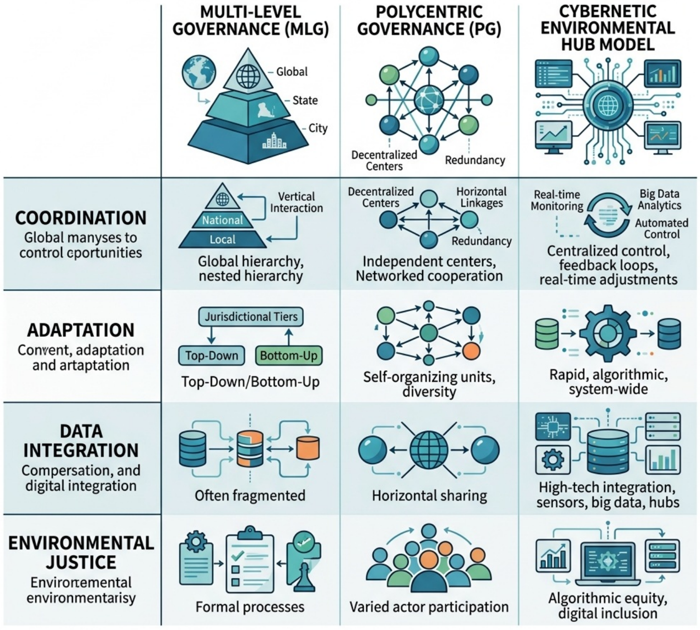

Figure 3. Comparative view of governance frameworks and their structural capabilities.

Beyond coordination, these frameworks frequently treat justice as a peripheral outcome rather than a structural baseline. Fakir (2023) highlights that the reliance on loans rather than grants in transition financing threatens to deepen debt burdens in emerging economies, shifting the transition's costs onto vulnerable populations [4]. Other critical analyses have found similar patterns, warning that top-down, opaque financing mechanisms can marginalize local voices and fail to deliver procedural or distributive equity [2,3]. Ultimately, without profound structural redesign, dominant transition agendas risk reproducing extractive patterns and neo-colonial dependencies under the guise of climate action [7].

2.4. Digital Governance and AIoT

To overcome these structural and informational bottlenecks, modern governance frameworks must seamlessly integrate advanced digital infrastructures. Liu (2026) establishes that Artificial Intelligence of Things (AIoT) and Early Warning Systems (EWSs) function as crucial "variety amplifiers," enabling local units to process high-frequency environmental data and trigger immediate algedonic feedback [14]. Studies have expanded this perspective by demonstrating that edge computing and distributed sensor networks allow real-time anomaly detection and autonomous operational management without overwhelming central authorities [17,38]. Therefore, embedding AIoT sensing directly into regulatory loops transforms technological platforms from passive IT tools into essential components of cybernetic adaptation [39].

Finally, the integration of these technologies demands rigorous and equitable open data governance architectures. McMahan et al. (2017) established the foundation of Federated Learning (FL), enabling machine learning models to be trained across decentralized devices without exchanging raw data [40]. Researchers have recently combined FL with blockchain-based smart contracts to ensure secure cross-domain collaboration, data sovereignty, and transparent incentive allocation, fundamentally preventing digital extractivism [18,20]. Thus, the literature confirms that coupling FAIR data principles with privacy-preserving, decentralized architectures provides the necessary trust and accountability mechanisms for resilient, justice-centered environmental governance [41].

3. Conceptual Development: The Viable Environmental Hub Model

3.1. Defining Environmental Hubs as Cybernetic Systems

Environmental Hubs are frequently conceptualized as technological clusters or coordination spaces for renewable energy deployment; however, this interpretation remains incomplete. Rooted in the neurocybernetic foundations established by Beer [22], this study reconceptualizes them as territorially embedded viable systems—recursive, adaptive, and normatively anchored governance architectures capable of sustaining just energy transitions. Subsequent studies have expanded this perspective, demonstrating that addressing complex socio-ecological turbulence requires fractal structures capable of simultaneously absorbing environmental variety and preserving systemic identity [27,28]. Therefore, the literature converges on the premise that true sustainability requires empowering local actors to manage their own environmental complexity while maintaining structural coupling with broader regional and national regimes [30].

We define Cybernetic Environmental Hubs (CEHs) as institutional–technical organs that transcend rigid hierarchical governance by integrating organizational cybernetics with advanced data infrastructures [42]. Rather than relying on centralized control, these hubs function as distributed regulatory architectures designed to amplify variety, coordinate decentralized actors, and steer regime-level socio-technical transitions [12,13]. Consequently, to operationalize these capabilities, a CEH acts as a meta-systemic organization that balances local operational autonomy with global ecological cohesion [10]. Figure 4 presents the conceptual architecture of the Cybernetic Environmental Hub.

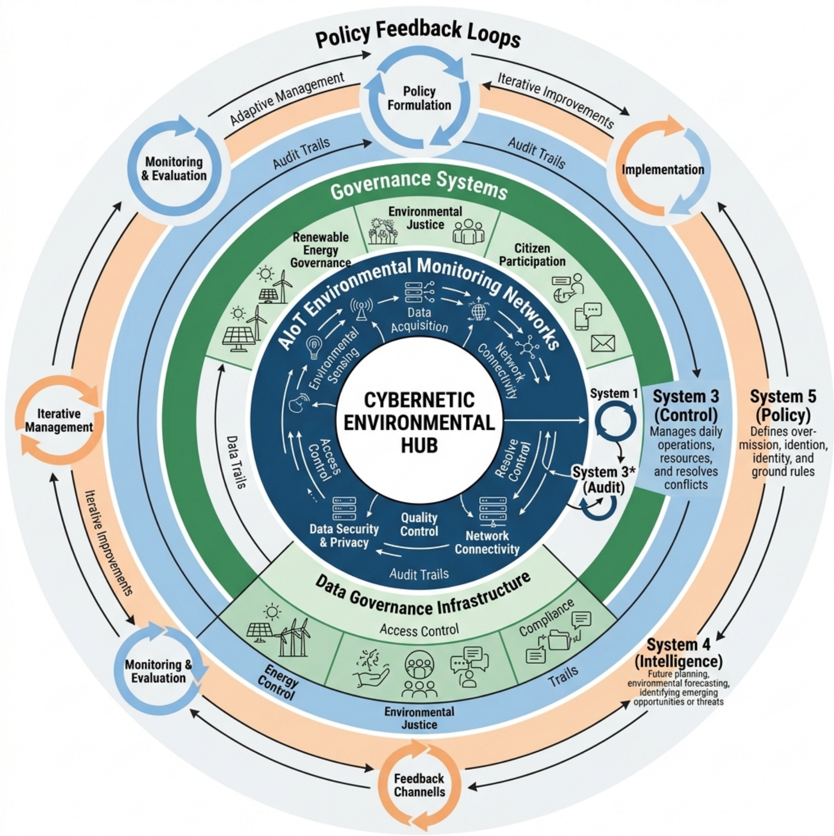

Figure 4. Conceptual architecture of the Cybernetic Environmental Hub (CEH). The figure layers (from bottom to top) AIoT sensing nodes (S1), blockchain coordination and federated-learning trust mechanisms (S2–S3), Early Warning Systems and digital twins (S4), and a justice-centered identity layer (S5). Solid lines denote physical/energy flows; dashed lines denote informational/regulatory flows. Four feedback loops are explicitly annotated: L1 S1↔S3 (operational compliance), L2 S3↔S4

(S3–S4 homeostat decoupling short-term optimization from long-term anticipation), L3 S4↔S5 (strategic identity), and L4 the algedonic bypass S1→S4 (response target < 60 s). Algedonic signals reach S4 directly when essential sustainability variables (e.g., $PM_{2.5} > 37\ \mu g/m^3$) are breached. Figure 5 provides a single-canvas overlay of these four loops together with the physical and informational flows.

To complement the layered view of Figure 4, Figure 5 provides an integrated single-canvas representation of the CEH in operation, overlaying physical energy flows, information flows, and the four feedback loops L1–L4 that govern adaptation. The diagram is intended to be read alongside Figure 4 (VSM mapping), Figure 6 (recursivity across territorial scales), Figure 7 (technology stack), and Figure 8 (data governance) so that readers seeking detail on any single subsystem can drill down without losing the integrated view.

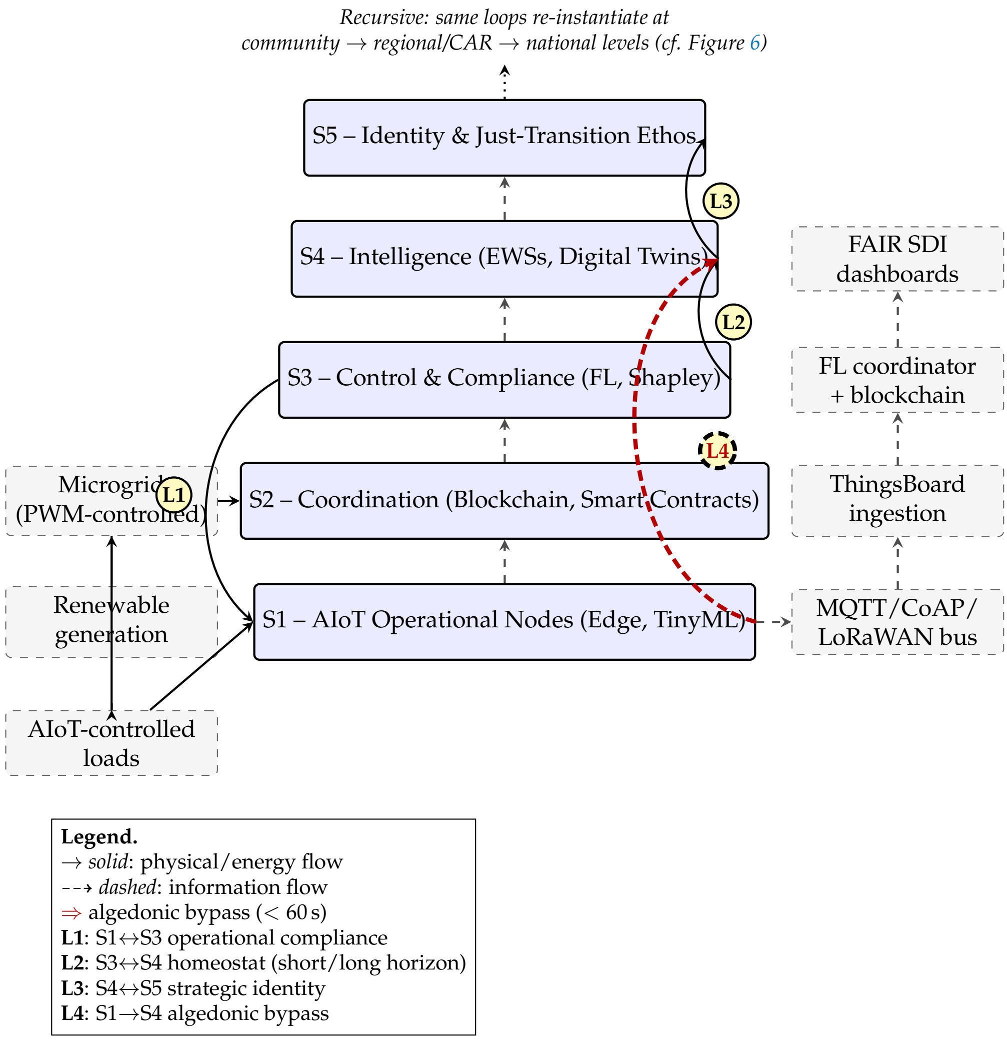

Figure 5. Integrated CEH operational diagram: physical energy flows (solid), information flows (dashed) and the four feedback loops L1–L4. The left column shows energy infrastructure (renewable generation → microgrid → AIoT-controlled loads); the right column shows the information stack (sensor → MQTT/CoAP/LoRaWAN bus → ThingsBoard → federated-learning coordinator + blockchain → FAIR SDI). Loops: L1 = S1↔S3 (operational compliance); L2 = S3↔S4 (S3–S4 homeostat decoupling short-term optimization from long-term anticipation); L3 = S4↔S5 (strategic identity); L4 = S1→S4 algedonic bypass (< 60 s). Cross-references: Figure 4 (VSM mapping), Figure 6 (recursivity), Figure 7 (technology stack), Figure 8 (data governance).

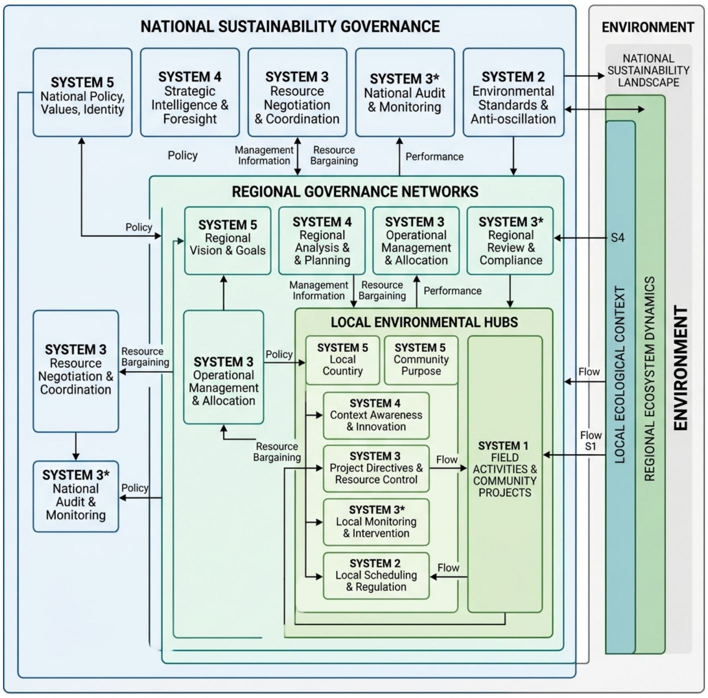

Figure 6. Recursive governance logic across territorial scales (community → regional/CAR → national). Each level repeats the S1–S5 architecture; only aggregated indicators and threshold alerts propagate upward, while raw data are retained locally under federated learning. Audit channels (S3*) operate within each level rather than across levels, preserving local autonomy.

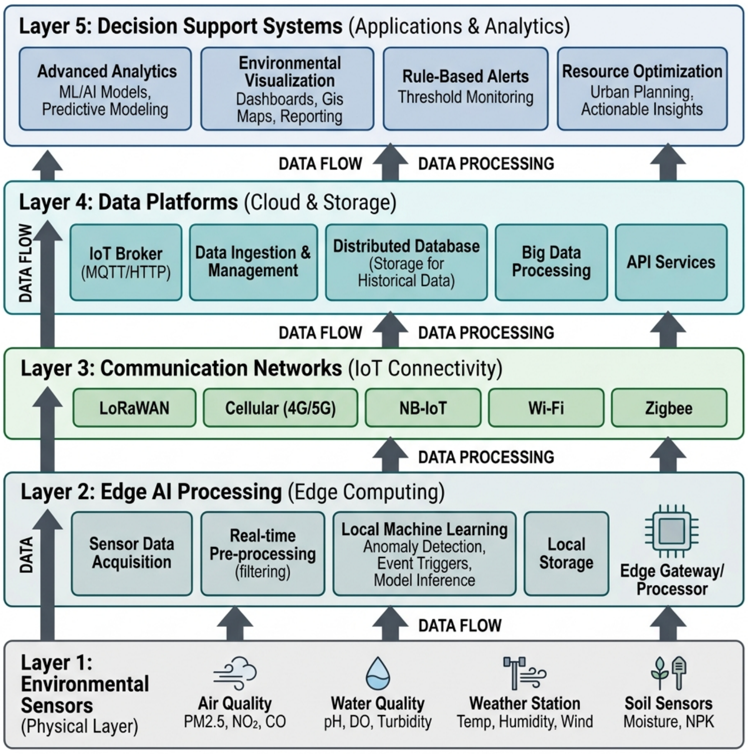

Figure 7. Socio-technical technology stack of the Cybernetic Environmental Hub. From bottom to top: edge AIoT (ESP32 microcontrollers; SPS30, SCD30, PmodMIC3 and SHT31 sensors); communication layer (MQTT/HTTP/CoAP over Wi-Fi, LTE and LoRaWAN); ingestion and storage (ThingsBoard hub, PostgreSQL); federated learning + blockchain trust layer; and FAIR-compliant SDI/dashboards. Algedonic-signal pathway: a $PM_{2.5}$ excursion at a sensor in Layer 1 propagates directly to S4 via the alert bus, bypassing routine S3 reporting (response target < 60 s).

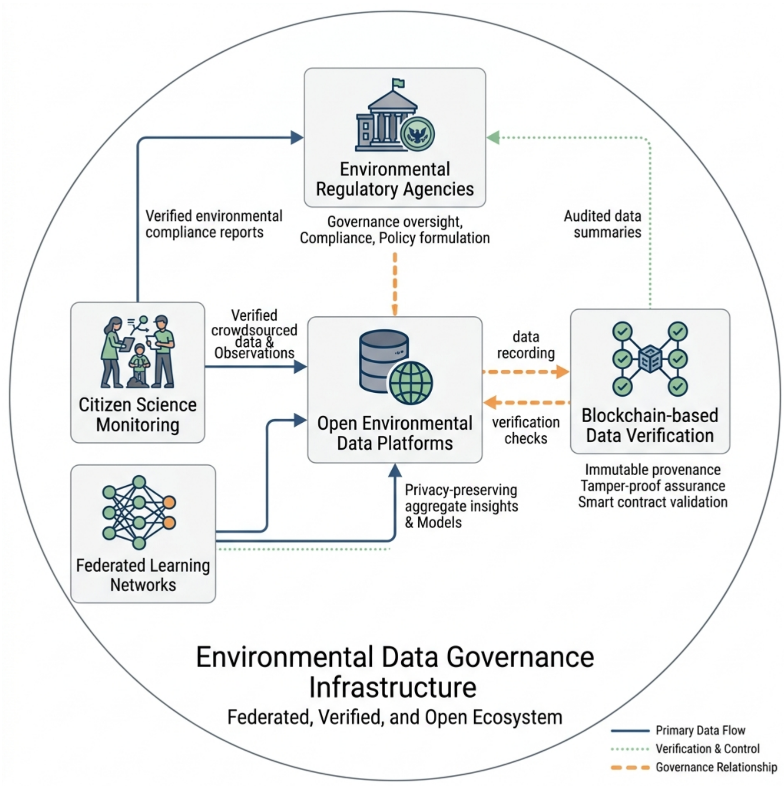

Figure 8. Data governance infrastructure for distributed CEH environmental monitoring. Federated learning keeps raw observations local (procedural justice); blockchain smart contracts log measurable contributions and trigger Shapley-value-based incentive allocation (distributive and algorithmic justice); FAIR-compliant SDI exposes only aggregated, non-sensitive metrics through public APIs (transparency).

3.2. Formal Application of VSM (Systems 1–5 Mapping)

Methodologically, the CEH is operationalized through a direct mapping of the five VSM subsystems (S1–S5) onto the socio-technical components of the Hub, ensuring functional completeness.

System 1 (S1): AIoT Operational Nodes—Responsible Autonomy. System 1 comprises the autonomous operational units responsible for primary activities, such as renewable energy generation, microgrid management, watershed stewardship, or territorial monitoring [24]. In the CEH architecture, S1 units are implemented as AIoT-enabled operational nodes utilizing edge computing. Edge AIoT enables local data processing and decision-making without continuous hierarchical intervention, thereby maximizing procedural autonomy and absorbing local environmental complexity in real time [38]. This design respects Ashby's Law of Requisite Variety by ensuring that operational complexity is managed at the level where it emerges [26].

System 2 (S2): Coordination Mechanisms—Anti-Oscillation and Equity. System 2 manages interdependencies among operational nodes, preventing oscillatory behavior and resolving shared resource conflicts [22]. In energy systems, this includes load balancing, frequency regulation, and dispute resolution over shared infrastructure. Technologically, S2 is supported by blockchain-based coordination protocols and smart contracts that transparently regulate energy exchange and resource allocation [20]. These mechanisms embed equity directly into the coordination logic by ensuring auditable, rule-based interactions among decentralized nodes [18].

System 3 (S3): Control and Compliance—Optimization and Data Sovereignty. System 3 ensures internal cohesion and real-time optimization, providing "here and now" governance [24]. Within CEHs, S3 supervises performance metrics, ensures compliance with sustainability thresholds, and allocates resources dynamically. Crucially, Federated Learning (FL) operationalizes S3 by enabling distributed model training across local devices without transferring raw data to central servers [17]. This protects privacy, prevents data extraction, and reinforces physical–social data sovereignty in Global South contexts, ensuring that S3 functions as both an optimization engine and a sovereignty safeguard [18]. To make "justice" tractable as a regulatory variable rather than a purely normative discourse, S3's optimization is parameterized through three computable layers: (i) distributive justice via multi-criteria allocation (e.g., TOPSIS/CRITIC-weighted node siting using socio-economic vulnerability, environmental exposure, and proximity to extractive activities); (ii) procedural justice via FL loss functions that keep raw community data local; and (iii) algorithmic justice via blockchain smart contracts implementing Shapley-value-based incentive allocation, so each node is compensated by its measurable marginal contribution of data, generation, or coordination effort [18,20].

These three computable justice layers are not parallel objectives but a lexicographic-with-floor composition over the federated-learning optimization. The procedural layer enters as a **hard constraint** of the System 3 problem: raw observations never leave the originating node, so any candidate policy that would require centralized data is infeasible by construction. Conditional on this constraint, the distributive layer enters as a TOPSIS/CRITIC-derived weight vector w_i over nodes (combining socio-economic vulnerability, environmental exposure and proximity to extractive activities), modulating the federated loss so that updates that improve aggregate efficiency at the expense of historically marginalized nodes are systematically down-weighted. The algorithmic layer then operates **ex post**: a Shapley-value-based smart contract redistributes incentives in proportion to each node's measurable marginal contribution of data, generation or coordination effort, closing the loop between effort and reward. Conflicts between dimensions—e.g., a sensing site that is optimal for predictive accuracy but suboptimal for distributive justice—are arbitrated by an equity-floor rule anchored in System 5: the optimization rejects any solution in which a justice dimension falls below a territorially negotiated threshold, even if it improves aggregate efficiency. In real-world deployments, these layers are quantitatively assessed through three operational metrics that integrate naturally with the H1–H3 rubric of Section 6 (the territorial maturity assessment rubric): (i) the **Gini index of incentive distribution** across participating nodes (algorithmic justice); (ii) the **federated-learning coverage rate**—the share of eligible nodes that successfully complete training rounds, disaggregated by socio-economic stratum (procedural justice); and (iii) the **demographic-parity gap** in algedonic-alert delivery times across community types (distributive justice). Together, these metrics make System 3's optimization auditable rather than purely normative [14,17,20].

System 4 (S4): Intelligence—Early Warning Systems and Climate Risk Analytics. System 4 represents the forward-looking intelligence function responsible for environmental scanning, scenario modeling, and long-term adaptation [21]. Within CEHs, S4 integrates AIoT sensors as Early Warning Systems (EWSs) that monitor essential sustainability variables (EVSs), such as grid stability, emissions thresholds, and socio-economic risk indicators [19]. When EVS thresholds are breached, these systems generate algedonic signals—immediate alerts that bypass bureaucratic inertia and trigger rapid adaptation pathways [14]. System 4 thereby transforms governance from reactive crisis management into proactive, predictive resilience planning. Within S4, an explicit event-horizon mechanism addresses the temporal asymmetry between long-life energy infrastructure (20–40 years) and short-life digital systems (3–5 years). Decoupling is achieved through (a) digital twins that simulate long-horizon infrastructure viability while absorbing fast-cycle hardware updates, (b) service-oriented APIs (REST/JSON) and FAIR-compliant

Spatial Data Infrastructures that stabilize the data layer across hardware generations, and (c) the S3–S4 homeostat, which separates short-term optimization (S3) from long-term anticipatory planning (S4) so that adaptive coherence is preserved across timescales [14,19].

System 5 (S5): Policy and Identity—Just Transition Ethos. System 5 defines the ultimate purpose and normative identity of the CEH, arbitrating the dynamic balance between current operations (S3) and future adaptation (S4) [30]. In this model, S5 embeds distributive, procedural, and restorative justice as non-negotiable pillars of governance. Normative commitments—such as the protection of vulnerable communities, ecological remediation, and the prevention of neo-colonial resource exploitation—filter all strategic decisions [7]. Open data governance frameworks further ensure transparency and accountability, anchoring the CEH in a justice-centered identity that prevents the transition from being co-opted by entrenched power asymmetries [43].

3.3. Recursive Architecture and Core Conceptual Integration

A fundamental property of the CEH model is its fractal recursivity, which allows the exact same S1–S5 functional architecture to operate consistently across multiple governance levels. This means that a local community microgrid (local S1) can be structurally aligned with provincial energy coordination (regional S2/S3) and national climate policy (national S5) while retaining its self-governance capacity [33]. This recursive design enables precise multiscale diagnostics and prevents the center–periphery power imbalances common in traditional top-down planning [28]. By nesting these viable systems, the framework ensures that normative justice commitments and adaptive intelligence flow seamlessly throughout the entire socio-ecological hierarchy [14]. The recursive governance logic across territorial scales is illustrated in Figure 6.

To make recursivity operational rather than purely theoretical, Figure 6 should be read alongside the following three-level walkthrough. Level 1 (community): An AIoT node hosts S1 (sensing and edge inference), S3* sporadic verification (local equipment monitoring), and a community S4 (local observatory issuing weather/air-quality alerts); raw data are retained locally under FL. Level 2 (regional/Corporación Autónoma Regional): Aggregated alert indicators travel upward via LoRaWAN gateways; S2 coordinates load and resource allocation across municipalities, S3* performs environmental compliance audits without extracting household-level records, and a regional S4 maintains an atmospheric digital twin. Level 3 (national): Aggregated indicators feed the IDEAM/SISAIRE air-quality system; S5 articulates climate policy (NDCs) and just-transition guidelines. The recursive interface principle is that variety is absorbed locally, while only aggregated indicators and threshold alerts propagate upward, preserving local autonomy and federated data sovereignty.

In the CEH framework, digital infrastructures behave as functional organs of a viable system rather than as add-ons. Edge AIoT devices act as sensory tissue and variety multipliers; Federated Learning and blockchain together form a decentralized trust layer that balances transparency with data sovereignty; and the S3–S4–S5 triad operates as a homeostat coupling internal control, anticipatory intelligence, and justice-centered identity [12,14,17,20,43]. By structurally coupling AIoT sensing, decentralized trust infrastructures, recursive governance design, and justice-centered identity, the Viable Environmental Hub model articulates a set of structural enabling conditions that are theoretically supportive of sustainable, legitimate, and adaptive just energy transitions, while empirical confirmation of their joint sufficiency requires comparative cross-territorial testing.

4. Socio-Technical Architecture

The socio-technical architecture of the Cybernetic Environmental Hub (CEH) operationalizes the conceptual model developed in Section 3 by structurally coupling AIoT-enabled sensing, Early Warning Systems (EWSs), decentralized trust infrastructures, and open environmental data governance. Rather than functioning as a mere digital overlay, this architecture constitutes the distributed nervous system of the Hub—amplifying requisite variety, enabling adaptive feedback, and embedding climate justice directly within the technical infrastructure.

Ning et al. (2024) establish the foundational role of decentralized data architectures in overcoming informational bottlenecks and enabling secure coordination across distributed environments [17]. Subsequent empirical studies demonstrate that integrating edge computing with Industrial Internet of Things (IIoT) infrastructures maximizes procedural autonomy by allowing operational nodes to process high-frequency environmental data locally without relying on continuous central intervention [38]. Therefore, distributed analytics ensure that sensing infrastructures remain structurally resilient, agile, and immune to the centralized points of failure common in traditional top-down environmental monitoring [39].

This AIoT monitoring layer forms the foundational operational substrate (System 1) of the CEH. It includes environmental sensors, smart meters, distributed renewable generation monitors, and socio-economic risk indicators deployed across territorial nodes. Rather than functioning as passive data collectors, these components operate as decentralized variety multipliers. By performing inference and anomaly detection at the edge, the system absorbs thousands of micro-perturbations—such as voltage fluctuations, localized pollution spikes, or demand variability—without overwhelming the higher meta-systemic governance layers.

The technological architecture supporting environmental hubs is presented in Figure 7. Data integrity at the origin is a critical design condition; sensor data must be cryptographically certified before transmission to prevent tampering, falsification, or poisoning attacks in distributed energy networks, ensuring that environmental monitoring remains both trustworthy and resilient [38].

The integration of Early Warning Systems (EWSs) functionally connects this operational monitoring (System 1) directly with anticipatory intelligence (System 4) through structured risk feedback loops. Liu (2026) establishes that within a cybernetic framework, EWSs function as algedonic signals—signals of extreme systemic stress that bypass bureaucratic inertia to trigger immediate regulatory responses [14]. When AIoT sensors detect that essential sustainability variables (EVSs), such as grid stability limits, air quality thresholds, or water stress indices, cross critical boundaries, these algedonic pathways are automatically activated.

This integration is further enhanced by digital twins, which allow institutions to simulate climate risk scenarios and regional infrastructure stress-tests in real time [19]. Consequently, the dynamic interaction between real-time risk sensing and predictive modeling forms a "Homeostat of Adaptation" that transforms governance from reactive crisis management into proactive resilience planning [30].

The final layer of the socio-technical architecture addresses the governance of environmental data. This is precisely where climate justice becomes materially encoded into the governance infrastructure, resolving the persistent tension between the need for global transparency and the imperative of local data sovereignty. Figure 8 illustrates the data governance infrastructure enabling distributed environmental monitoring.

McMahan et al. (2017) established the methodological foundation of Federated Learning (FL), which enables advanced machine learning models to be trained collectively across decentralized nodes without ever transferring raw data to centralized servers [40]. Within the CEH architecture, FL preserves community sovereignty over sensitive "physical-social" data—preventing data extractivism and digital colonialism in the Global South—by sharing only encrypted model gradients [20]. Furthermore, blockchain technology provides an immutable trust layer that guarantees transparency in climate finance flows and automates fair compensation schemes.

Smart contracts can implement transparent reward distribution based on measurable community contributions, such as surplus renewable energy generation or participatory data collection, effectively eliminating predatory intermediation [18]. Thus, integrating privacy-preserving FL with blockchain-based cryptographic accountability guarantees that distributive and procedural justice are embedded as structural technical constraints rather than contingent political choices [41].

Finally, while FL protects sensitive community data, aggregated insights and macro-level environmental metrics must be governed under open frameworks to ensure institutional legitimacy. The CEH architecture mandates that non-sensitive datasets comply with FAIR principles (Findable, Accessible, Interoperable, and Reusable) through a community-based Spatial Data Infrastructure (SDI) [14]. The SDI ensures that climate data and governance dashboards remain publicly accessible, fostering citizen science co-creation and providing independent oversight of transition policies.

In summary, this layered socio-technical stack ensures that the CEH is not a disparate assemblage of IT tools but a structurally integrated cybernetic system. The base layer provides edge-processed operational autonomy (System 1); the blockchain and FL layer ensures secure coordination and data sovereignty (Systems 2/3); the EWS and digital twin layer delivers predictive risk intelligence (System 4); and the FAIR SDI layer guarantees justice-centered transparency (System 5). By embedding justice, resilience, and sovereignty into the technical substrate, the architecture ensures that Environmental Hubs possess the requisite variety to govern just energy transitions effectively.

4.1. Concrete Operational Deployment in the Caribbean Mining Corridor

To move beyond a purely conceptual description, the architecture above is grounded in an actual cyber-physical deployment carried out under project BPIN 2023000100072 (SGR/MinCiencias Call 31). The CEH's System 1 layer comprises approximately 90 AIoT environmental monitoring stations distributed across Albania (La Guajira), La Jagua de Ibirico (Cesar) and Algarrobo (Magdalena). Each station integrates particulate sensors (SPS30 for $PM_{10}/PM_{2.5}$), CO_2 sensors (SCD30), acoustic sensing (PmodMIC3), and temperature/humidity sensors (SHT31), all governed by ESP32 microcontrollers performing edge pre-processing and TinyML-based anomaly detection. The communication stack combines MQTT, HTTP and CoAP over Wi-Fi, LTE and LoRaWAN—the latter being critical for nodes located beyond reliable cellular coverage, with effective rural ranges of 15–20 km. Data ingestion is handled by a ThingsBoard IoT hub, while a PostgreSQL backend supports open data APIs (CSV/JSON dashboards and FAIR-compliant SDI services). This deployment turns the CEH from an abstract architecture into a working cyber-physical instrument whose engineering choices can be scrutinized, replicated, and stress-tested.

4.2. Operationalizing Justice: Worked Examples

Two short worked examples illustrate how the "justice-centered ethos" is encoded into specific socio-technical mechanisms rather than left at the level of normative aspiration. (a) Technical example (S2–S3). A community AIoT cluster contributes data to a federated training round of an air-quality forecasting model. Raw observations never leave the cluster (procedural justice). A blockchain smart contract logs each cluster's measurable contribution—data volume, model-quality improvement, sensor uptime $> 95\%$—and computes a Shapley-value-based reward that is automatically distributed in tokens or local-currency credits, with a full audit trail [17,18,20]. (b) Institutional example (S2–S5). When a national decarbonization target conflicts with an indigenous community's "Plan de Vida," resolution is routed through citizen oversight committees (veedurías) and intercultural mediation panels acting at the boundary between regional S5 and national S5 of the recursive structure, rather than overridden by upper-level optimization [30,33]. Together these examples make it explicit that the CEH treats both distributive and procedural justice as executable design constraints, while reserving conflict resolution to deliberative institutional mechanisms.

4.3. Requisite Variety, Thermodynamic Efficiency and Cross-Sector Applicability

A legitimate concern raised in the review process is whether the CEH increases internal variety—and therefore entropy and energy cost—beyond the savings it enables. Our design response is to distribute rather than concentrate variety. Edge AIoT and TinyML perform local inference, so the bulk of micro-perturbations (voltage fluctuations, particulate spikes, acoustic anomalies) are absorbed at the edge [14,26]. Only sparse aggregated signals—algedonic alerts and KPI summaries—propagate upward, drastically reducing communication overhead and the energy cost of cloud round-trips. In the deployed network this strategy is reinforced by adaptive PWM-based control of public-lighting nodes, whose measured energy savings are designed to outweigh the marginal computational cost of the distributed sensing layer.

To make this argument quantitatively auditable rather than rhetorical, we make the underlying energy budget explicit. Each S1 node combines an ESP32-class microcontroller with the SPS30/SCD30/PmodMIC3/SHT31 sensor stack and operates at approximately 0.1–0.4 W in active duty and below 50 mW in TinyML duty-cycled mode; routine maintenance comprises annual sensor calibration, battery replacement every 2–4 years ($LiFePO_4$ chemistry), and firmware-over-the-air updates whose energy footprint is dominated by transmission rather than compute. Against this consumption profile, the architecture targets three converging savings flows: (a) the adaptive PWM-based control of public-lighting nodes (15–30% reduction over fixed-schedule baselines, consistent with the literature cited); (b) the avoided cloud round-trips enabled by edge inference and federated aggregation (estimated at one to two orders of magnitude in upstream bytes); and (c) the avoided over-provisioning of grid and water infrastructure obtained when EWS-driven anticipatory action displaces reactive crisis response. The "net energy-positive at the territorial scale" condition is therefore defined as a design requirement that the sum of measurable sectoral savings (a)–(c) exceed the active-duty consumption of the sensing-and-compute layer plus the amortized embodied energy of replacement hardware over its service life. Verification is operationalized through the technological-dimension proxies of the H1→H3 rubric so that progress toward H3 directly indexes progress toward a net-positive territorial energy balance rather than asserting it ex ante.

The same reasoning makes the architecture technology-agnostic and recursive: refrigeration and cold-chain fleets in the Global South (food security, vaccine storage, rural electrification) can be reframed as S1 nodes whose load coordination (S2), efficiency-and-fairness optimization (S3), predictive maintenance (S4) and food-security-oriented policy (S5) inherit the CEH's H1–H3 maturity logic without redesigning the framework. To make the recursive applicability concrete, Table 1 specializes the H1–H3 maturity rubric to refrigeration and cold-chain fleets, preserving the four dimensions of the territorial maturity assessment rubric (Technological, Institutional, Data Governance, Justice) while replacing each proxy with a fleet-specific operational measure.

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Table 1. Cold-chain and refrigeration fleets: specialization of the H1–H3 maturity rubric (recursive S1-node application of the territorial maturity assessment rubric.

Dimension	H1—Operational	H2—Optimization	H3—Reinvention
Technological	% of units with continuous telemetry (temperature, door-events, GPS); manual reporting only.	Mean time-to-alert on thermal excursions < 10 min; gateway availability $> 95\%$; predictive analytics on cooling cycles.	Autonomous closed-loop compensation < 60 s; fleet-wide federated learning for predictive maintenance; algedonic alerts on critical cargo.
Institutional	Bilateral operator–health-authority agreements only; no anti-oscillatory mechanism.	Polycentric S2 coordination across operators (load and route rebalancing); formal cold-chain integrity protocols.	Community veto rights formally codified for essential cargo (vaccines, staple foods); integrity audits embedded in S5.
Data Governance	No public traceability of cold-chain integrity; centralized vendor logs.	FAIR-aligned APIs; public dashboards; refresh interval ≤ 15 min; sensor uptime $> 95\%$.	Federated learning across fleets; blockchain smart contracts logging maintenance and Shapley-based settlement of inter-operator coordination.
Justice	Routes systematically exclude remote/low-income communities; spoilage borne by end-users.	TOPSIS/CRITIC siting and routing using nutritional and health-vulnerability indices.	Shapley-allocated incentives for service to high-vulnerability nodes; community veedurías over spoilage and cold-chain losses.

Retrospective assessment for cold-chain fleets is operationalized by applying this rubric to 12–24 months of historical operational records (telemetry archives, maintenance logs, rejection-and-spoilage rates, and route data), establishing a baseline H-score per dimension prior to any CEH intervention. Progress is then tracked by re-scoring at fixed intervals against the same proxies so that operators and regulators can read fleet-level maturity changes in the same units used for territorial maturity in Section 6.

4.4. Infrastructural Feasibility and Low-Tech Fallbacks

The Caribbean Mining Corridor presents intermittent grid electricity, sub-4G coverage in rural nodes, dust- and humidity-related device wear, and a non-trivial digital-literacy gap. The CEH is engineered for these conditions rather than against them. Hybrid connectivity (Wi-Fi + LTE + LoRaWAN with delay-tolerant queuing) sustains data continuity under partial outages; nodes are powered by hybrid solar + battery configurations and energy-harvesting designs, and TinyML keeps active-cycle consumption below typical IoT baselines. Anti-dust/anti-humidity enclosures and tamper-evident housings address environmental and security wear. Digital-literacy gaps are mitigated through a "train-the-trainers" model anchored in local universities and CARs, multimodal interfaces, and—crucially—an explicit low-tech fallback layer co-designed with communities: SMS-based alerts, community-radio bulletins, megaphone protocols, and printed risk maps for situations in which the AIoT layer is unavailable. The CEH therefore does not assume idealized infrastructure; it embeds graceful degradation as a first-class design property.

5. Methodological Validation

Fathi et al. (2025) establish the methodological framework for validating cybernetic governance models through real-world socio-ecological diagnostics [19]. Empirical studies corroborate this by demonstrating that systemic validation requires moving beyond conceptual modeling to the formal structural mapping of organizational pathologies [44]. Consequently, the methodological design of this study applies a hybrid conceptual–empirical approach to translate the theoretical propositions of the Cybernetic Environmental Hub (CEH) into territorial diagnostic processes [31]. The empirical application detailed in this section functions as an illustrative, single-site qualitative validation of the architectural design rather than a statistical generalization. Its purpose is to examine whether cybernetic mapping can plausibly operationalize complex sustainability challenges into actionable institutional diagnostics, not to prove the universal applicability of the framework.

The research design follows a rigorous sequential methodology integrating participatory data collection with formal cybernetic mapping. The methodological workflow adopted in this study is summarized in Figure 9. The process begins with case study selection, followed by the participatory elicitation of socio-ecological challenges. These narrative challenges undergo qualitative thematic coding and are subsequently clustered into systemic archetypes. Finally, these archetypes are analytically mapped onto the Viable System Model (VSM) functional subsystems, allowing researchers to diagnose "variety gaps" and propose targeted socio-technical interventions. This workflow ensures that theoretical abstractions remain deeply anchored in territorial realities.

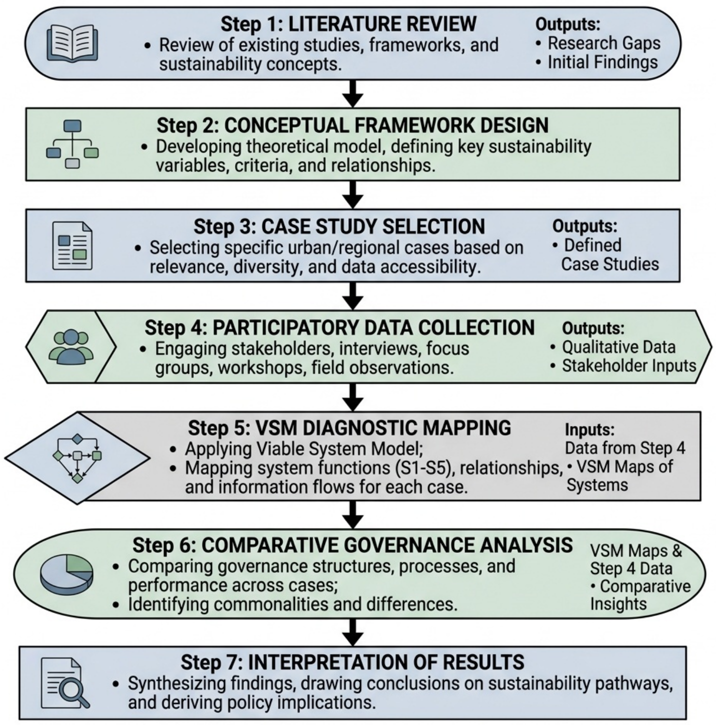

Figure 9. Sequential methodological workflow for participatory cybernetic validation.

Jain and Bustami (2025) establish that evaluating energy transition governance requires confronting the structural constraints, fiscal limitations, and high-complexity environments typical of the Global South [1]. Subsequent studies have expanded this perspective, showing that extractive regions—such as the Caribbean Mining Corridor selected for this study—exhibit profound socio-ecological fragmentation, multi-level coordination deficits, and historical power asymmetries that undermine cooperative transition initiatives [2]. In this territory, traditional community-based authorities frequently operate through informal horizontal arrangements that coexist uneasily with formal state bureaucracies. Furthermore, socio-ecological challenges transcend political-administrative boundaries, creating an ecological–institutional mismatch. Therefore, the literature converges on the premise that such highly turbulent territories, where the "system in focus" must be defined by actual ecosystem boundaries rather than rigid bureaucratic jurisdictions, represent the optimal empirical testing ground for recursive governance redesign [3].

Espinosa (2022) establishes that self-transformation methodologies must be anchored in participatory, bottom-up diagnostics to accurately capture the operational reality of marginalized communities [30]. The empirical dataset for this validation, the Banco de Retos I+D+i, operationalizes this principle as a participatory repository of territorial challenges compiled through extensive community workshops and collaborative innovation processes. Other authors have found similar results in comparable contexts, noting that structured social learning spaces act as vital platforms for co-producing knowledge and articulating complex socio-ecological dysfunctions that top-down technocratic audits frequently overlook [11].

To improve methodological auditability, we make the participatory protocol explicit. The Banco de Retos I+D+i was populated through three Design-Thinking workshops (Empathize–Define–Prioritize phases), each lasting at least four hours: two in La Guajira (Albania and Riohacha, 12 September 2025) and two in Magdalena/Cesar (Algarrobo and La Jagua de Ibirico, 24 October 2025). The sessions gathered more than 30 participants per round, recruited through a quadruple-helix logic, including indigenous representatives, community leaders, rural teachers, municipal governments, regional environmental authorities (CARs Corpoguajira and Corpocesar), mining-sector actors and civil-society organizations. Coding followed a Participatory Action Research (PAR) plus Design-Thinking framework rather than software-mediated coding: a six-component co-creation canvas (problem, challenge, characteristics, criteria, model, value generation) functioned as a live axial coding matrix, with researchers acting as facilitators and validators. An initial pool of 18 candidate challenges was reduced to 9 validated priorities through member-checking assemblies (24 October 2025), explicitly applying negative-case analysis to avoid forcing community narratives into VSM categories. Verbatim diagnostic excerpts are reported in Table 2, while the full coding canvas, audit trail and member-checking notes are made available as Supplementary Material rather than expanded in the main text.

Consequently, the qualitative narratives from the Banco de Retos were subjected to thematic coding into specific "diagnostic points" (D1, D2, ..., Dn) and subsequent cluster analysis. This approach translated fragmented community grievances into systemic indicators, revealing underlying organizational archetypes [12].

The core of the validation process consisted of mapping these clustered challenges to the five VSM subsystems (S1–S5), thereby transforming descriptive territorial complexity into candidate design insights. Figure 10 shows how territorial governance challenges were mapped into the subsystems of the Viable System Model. This analytical translation process allows structural vulnerabilities to be systematically categorized and matched with CEH technological mitigations. For instance, localized challenges regarding overloaded community leaders and highly fragmented renewable initiatives were mapped to System 1 (Operations) and System 2 (Coordination). These clusters revealed anti-oscillation deficits, which the CEH framework aims to mitigate through edge AIoT automation tools and blockchain-enabled coordination protocols [45].

To improve the transparency and reproducibility of the qualitative coding process, Table 2 provides illustrative examples of the coding pipeline used in this study. Each row shows a redacted excerpt of a community-reported challenge from the Banco de Retos I+D+i, the thematic code assigned during open coding, the cluster obtained during axial aggregation, and the VSM subsystem to which the cluster was mapped. The table is intended as an illustrative sample (not an exhaustive codebook) and is designed to make the inferential chain from narrative to subsystem mapping auditable.

Table 2. Illustrative mapping from community-reported challenges to codes, clusters, and VSM subsystems.

Challenge ID	Redacted Excerpt	Open Code	Cluster (Axial)	VSM Subsystem
D1	"Low level of digital literacy in the community; people struggle to interpret technical environmental data."	Community appropriation deficit	Operational overload & capacity deficit	S1
D2	"Each NGO and project installs its own sensors; there is no shared protocol or data model."	Sensor fragmentation	Interoperability & anti-oscillation gap	S2
D3	"We perceive that environmental data are manipulated, or are simply inaccessible to citizens."	Trust & transparency deficit	Control & accountability deficit	S3
D4	"External teams use our data for reports that never come back to us."	Data extractivism	Data sovereignty & open data deficit	S3/S3*
D5	"There is no robust local environmental monitoring; floods and heat waves always catch us by surprise."	Absence of EWS	Foresight & EWS gap	S4
D6	"Transition plans are written in the capital without us; we only learn about them afterwards."	Procedural exclusion	Normative identity & justice misalignment	S5
D7	"Benefits from renewable projects go to companies; local communities receive almost nothing."	Distributive injustice	Justice-centered identity gap	S5

Similarly, missing audit mechanisms and limited institutional monitoring capacity were diagnosed as System 3 (Control) failures, highlighting the need for Federated Learning architectures and transparent, FAIR-compliant data dashboards [44]. Furthermore, reactive climate responses and the absence of anticipatory planning were identified as System 4 (Intelligence) bottlenecks, directly justifying the integration of AIoT-based Early Warning Systems (EWSs) and digital twins [19]. Finally, conflicting transition narratives and the lack of a shared vision of climate justice pointed directly to normative identity fractures within System 5 (Policy and Identity), demonstrating the necessity of a justice-centered governance framework [10].

This diagnostic mapping revealed a recurrent structural asymmetry also reported in comparable Global South settings: strong informal operational dynamism (S1) coexisting with more fragile, reactive meta-systemic coordination (S2–S4). By aligning participatory diagnostics with the functional requirements of the VSM, the CEH model transitions from a theoretical proposition into an evidence-informed instrument for institutional diagnostics. The Caribbean Mining Corridor thus serves not as rigorous empirical proof but as an illustrative case suggesting that the framework can help diagnose, and inform the redesign of, complex territorial governance dysfunctions.

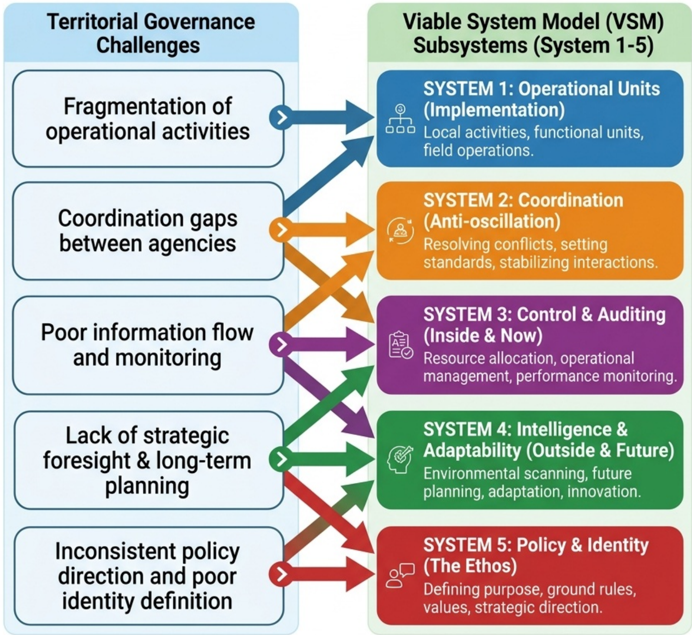

Figure 10. Diagnostic mapping of territorial governance challenges in the Caribbean Mining Corridor to VSM subsystems. Verbatim community-reported challenges (Banco de Retos I+D+i, see Table 2) are clustered into archetypes and mapped to S1–S5: digital-literacy gaps and overloaded leadership → S1; sensor and protocol fragmentation → S2; opaque environmental compliance and data extractivism → S3/S3*; absence of robust monitoring and EWS → S4; procedural exclusion and distributive injustice → S5.

6. Territorial Maturity Model (H1–H3)

The Territorial Maturity Model (H1–H3) extends the Cybernetic Environmental Hub (CEH) framework by introducing a diagnostic instrument to assess the evolutionary stage of socio-ecological governance systems. Orr and Burch (2025) establish that territorial maturity is not a linear metric of technological adoption, but rather the progressive development of systemic learning capacities and transformative reflexivity [12]. Subsequent studies expand this perspective, showing that true maturity reflects the extent to which a territory can actively absorb environmental variety and coordinate institutional complexity from the bottom up [14,30]. Therefore, systemic maturity requires a cybernetic evolution—moving from reactive, single-loop survival toward proactive reinvention and structurally embedded justice [21].

To operationalize this diagnostic capacity, the model defines three evolutionary stages: H1 (Fragmented Governance), H2 (Coordinated Governance), and H3 (Cybernetic Governance). The proposed territorial governance maturity model is illustrated in Figure 11. Lederer et al. (2025) note that at the H1 (Operational) level, systems exhibit single-loop learning, relying heavily on informal arrangements and reactive adaptation where System 1 units are highly dynamic but meta-systemic coordination remains weak [10]. Double-loop learning emerges at the H2 (Optimization) stage, where coordination mechanisms (System 2) and strategic foresight (System 4) become formalized, significantly reducing transaction costs and improving resource allocation [12,30]. Ultimately, H3 (Reinvention) represents the attainment of ecological reflexivity, where the territory approaches a dynamic homeostasis between operational autonomy and a justice-centered identity (System 5), understood as a set of enabling conditions theoretically associated with long-term viability rather than as strictly necessary and sufficient conditions [19].

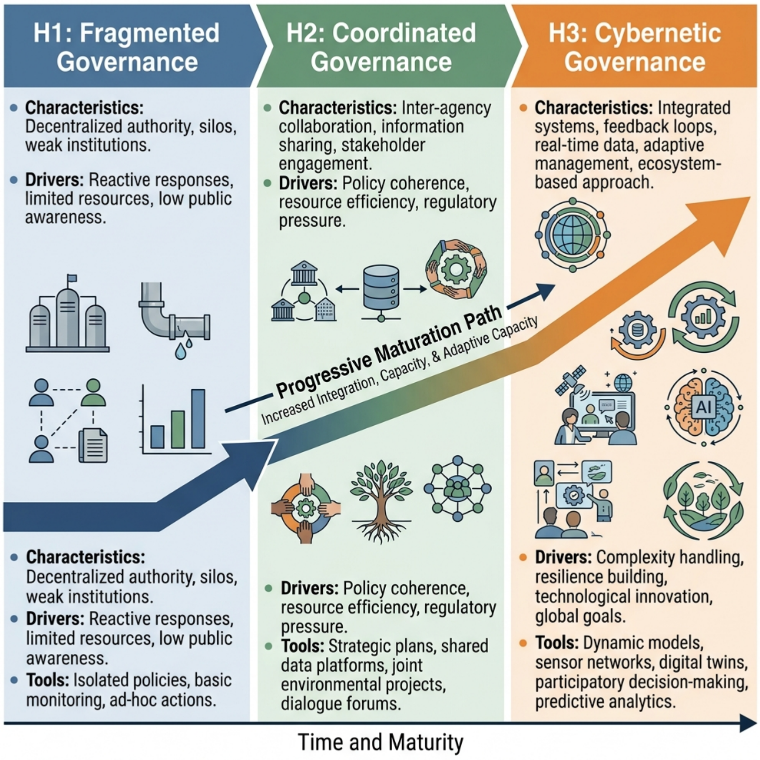

Figure 11. Territorial governance maturity model (H1–H3).

6.1. Territorial Maturity Assessment Matrix

This maturity progression is mapped across four critical dimensions (Table 3): Technological, Institutional, Data Governance, and Justice Integration. Ning et al. (2024) establish that technological and data governance must evolve from passive extraction toward decentralized, privacy-preserving infrastructures such as Federated Learning [17]. This technological evolution must be strictly matched by institutional and normative shifts, ensuring that blockchain-enabled smart contracts distribute systemic incentives transparently and equitably [18,20]. Consequently, progression toward H3 requires that distributive and procedural justice transition from being contingent political compensations to becoming structurally encoded features of the governance architecture [43].

Table 3. Territorial Maturity Assessment Rubric with quantifiable proxies and retrospective scoring (Caribbean Mining Corridor baseline).

Dimension	H1—Operational	H2—Optimization	H3—Reinvention	CMC Score
Technological	Isolated sensors; basic data collection; information silos [45]. Proxies: sensor count $< 10/100\,km^2$; manual reporting only.	Integrated EWS; predictive analytics; digital twins for crisis modeling [19]. Proxies: EWS alert latency < 10 min; $PM_{2.5} > 25\,\mu g/m^3$ threshold monitored.	Autonomous cyber-physical orchestration; Edge AI processing algedonic signals in real time [14]. Proxies: EWS alert latency < 60 s; $PM_{2.5} > 37\,\mu g/m^3$ (Res. 2254/2017) and PM_{10} $> 75\,\mu g/m^3$ thresholds; protocols MQTT/CoAP/LoRaWAN.	2/5

Table 3. *Cont.*

Dimension	H1—Operational	H2—Optimization	H3—Reinvention	CMC Score
Institutional	Fragmented governance; hierarchical or informal arrangements [10]. Proxy: % of inter-municipal coordination agreements formally signed.	Polycentric coordination; formal anti-oscillatory mechanisms (System 2) [30]. Proxy: S2 reduces resource-conflict events $\geq$ 30% year-on-year.	Emancipatory cybernetic governance; recursive autonomy with global cohesion [13,43]. Proxy: community veto-rights formally codified in S5.	2/5
Data Governance	Passive data extraction; centralized repositories controlled externally [19]. Proxy: no public dashboards; data update > 90 days.	Adoption of FAIR principles; community Spatial Data Infrastructure (SDI) [14]. Proxy: FAIR-aligned APIs; refresh interval $\leq$ 15 min; sensor uptime > 95%.	Federated Learning + Blockchain ensuring data sovereignty and just incentive allocation [17,20]. Proxy: % of nodes under FL training; smart-contract execution rate > 0.	1/5
Justice	Just transition framed as a peripheral compensation mechanism [15]. Proxy: housing deficit (e.g., 36.75% in La Jagua) not factored into siting decisions.	Procedural inclusion; participation of affected groups in rule formation [10]. Proxy: TOPSIS/CRITIC node siting using vulnerability indices.	Structural and distributive justice embedded as systemic identity (System 5) [7,18]. Proxy: Shapley-value-based incentive allocation operational; veedurías active.	2/5

Applying the rubric retrospectively to the Caribbean Mining Corridor yields an aggregate baseline of **7/20**, consistent with an H1-dominant territory exhibiting partial H2 elements (incipient EWS, some inter-institutional coordination via CARs) but no H3 features yet (no operational FL training, no Shapley-based incentive contracts). This score is not a definitive metric but a worked illustration of how the rubric can be used as a diagnostic instrument and how progress toward H2/H3 can be tracked over the project's implementation horizon.

6.2. Positioning the Case: Empirical Evaluation

Applying this assessment matrix to the Caribbean Mining Corridor reveals a structural bottleneck typical of Global South settings. Figure 12 positions the case study within the proposed territorial governance maturity model. Pérez-Matamoros et al. (2025) demonstrate that such resource-dependent territories often exhibit robust System 1 dynamism, characterized by strong informal trust-based networks and localized renewable initiatives, placing their baseline functionality at the H1 level [45]. However, these grassroots operations face severe meta-systemic fragilities, particularly the absence of structured coordination (System 2) and anticipatory intelligence (System 4), which stymies natural progression to H2 optimization [19,30]. Therefore, introducing the CEH architecture—with its AIoT variety amplifiers and decentralized trust protocols—acts as a cybernetic catalyst, enabling the territory to bypass traditional bureaucratic stagnation and leapfrog directly toward H3 systemic reinvention [14].

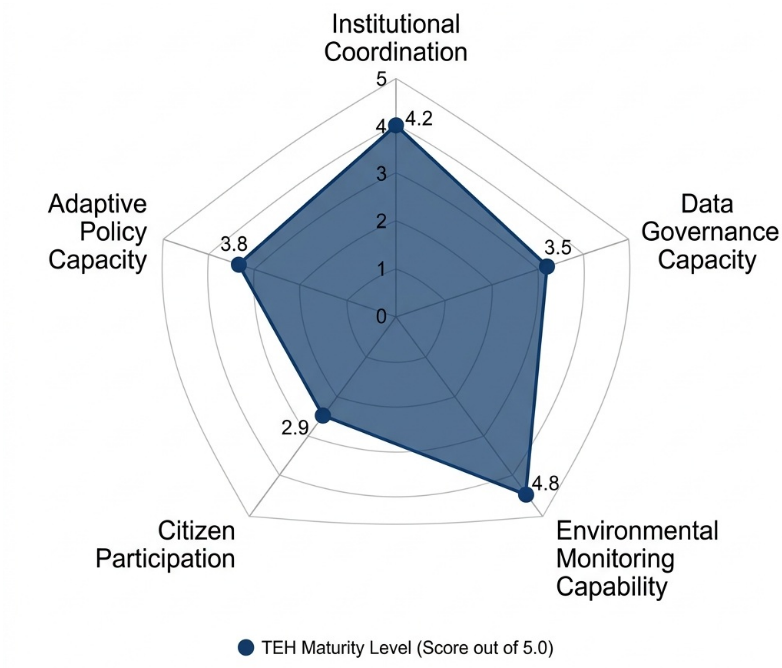

Figure 12. Case positioning within the territorial maturity model.

By embedding technological infrastructure within a recursive governance and justice-centered identity framework, this maturity model suggests that advancing the energy transition is not merely a matter of rapid digitalization but also an issue of structural viability and emancipatory transformation in the Global South, a proposition that this article frames as a testable design hypothesis rather than an established empirical fact.

7. Comparative Governance Analysis

This section positions the Cybernetic Environmental Hub (CEH) model within the broader landscape of energy and climate governance frameworks. Rather than rejecting existing approaches—such as Polycentric Governance (PG), Multi-Level Governance (MLG), Adaptive Governance, or Transition Management (TM)—the Viable System Model (VSM)-based CEH reframes and structurally integrates their strengths within a prescriptive cybernetic architecture. Lederer et al. (2025) establish that while PG and MLG have significantly advanced our understanding of distributed authority and network-based coordination, they frequently encounter high transaction costs and risks of ineffective fragmentation at macro-scales [10]. Subsequent studies have expanded this perspective, showing that global climate governance often suffers from "theoretical fragmentation," where coordination becomes dependent on voluntary alignment rather than structural design [14]. Other authors note that Adaptive Governance and TM, while fostering resilience and niche innovation, frequently lack the formal multi-level architecture needed to restructure entire institutional regimes [12]. Therefore, the literature converges on the necessity for an integrated framework that moves beyond descriptive coordination toward normative systemic viability.

The primary added value of the CEH lies in shifting from descriptive sustainability toward mathematically grounded systemic viability. Figure 3 synthesizes the differences between the proposed framework and existing governance approaches. Unlike conventional models, the CEH explicitly integrates high-speed systemic feedback, continuous digital monitoring, and adaptive governance into a unified architecture, addressing the critical gaps identified in the literature. By structurally coupling AIoT, predictive intelligence, and decentralized trust mechanisms, it provides the institutional "plumbing" required to translate normative ideals—such as climate justice and participatory legitimacy—into structurally embedded governance mechanisms [13].

A fundamental distinction of the CEH is its approach to structural coherence. The VSM differs from descriptive frameworks by providing a prescriptive structural skeleton that guarantees coordination (Systems 2 and 3) without sacrificing local operational autonomy [10]. Unlike rigid command-and-control hierarchies or loosely coupled informal networks, the VSM's fractal recursivity ensures that policy coherence translates fluidly from global agreements to regional authorities and down to community microgrids [45]. Structural coherence is therefore engineered rather than assumed.

Furthermore, conventional governance systems typically operate through linear planning cycles and delayed evaluation mechanisms, rendering their crisis responses bureaucratically slow and reactive. The VSM, by contrast, is intrinsically designed around high-speed feedback loops. The institutionalization of algedonic signals—early warning alarms that bypass traditional hierarchies—allows operational disturbances (such as grid instability or water supply shocks) to directly activate strategic response mechanisms [22]. The continuous adaptation homeostat linking internal control (System 3) and strategic intelligence (System 4) enables rural communities to transition from reactive crisis management to proactive, agile governance [30]. Feedback is not episodic but structural.

The integration of climate justice represents another critical divergence. In many contemporary climate finance mechanisms, including Just Energy Transition Partnerships (JETPs), justice is frequently treated as a peripheral outcome or compensatory add-on, often prioritizing loans over grants and limiting distributive equity [1,15]. In contrast, the VSM embeds justice as a structural condition of viability within System 5, which defines the system's identity, purpose, and normative commitments [14]. To address critiques of classical cybernetics regarding power blindness, the CEH design incorporates a "power-aware VSM," actively diagnosing visible, hidden, and invisible power asymmetries in energy transition decision-making [43]. Justice thus becomes an institutionalized design dimension rather than a political afterthought.

Finally, many governance frameworks treat digital technologies as external instruments rather than integral structural components. The CEH framework provides a precise architectural blueprint for embedding AIoT, Edge AI, Federated Learning, and Blockchain as functional organs of the governance system [19]. The formalization of an Intelligence function (System 4) distinguishes the VSM from descriptive frameworks by integrating predictive analytics and digital twins, enabling anticipatory adaptation rather than retrospective evaluation [14]. Moreover, the structural integration of Federated Learning and blockchain-based smart contracts ensures data sovereignty, privacy, and fair incentive schemes, actively preventing digital extractivism in the Global South [17,20]. Digitalization, under the VSM, becomes systemic rather than cosmetic.

In summary, the CEH model is framed as complementary to Polycentric and Multi-Level Governance rather than as a replacement: it offers a cybernetic scaffolding that can render their coordination premises more operational. By providing an architecture that integrates structural coherence, high-speed feedback loops, justice-centered identity, and predictive digital intelligence, the CEH model advances beyond descriptive coordination networks toward a candidate viable socio-technical governance architecture. Whether this architecture constitutes a set of sufficient conditions for just energy transitions in the Global South is an empirical question that this paper does not claim to have settled; it identifies a coherent set of structural enabling conditions that warrant comparative testing.

7.1. Decolonial Engagement and Power-Aware Cybernetics

A frequent critique of cybernetic governance is that, originating from a Western neurophysiological metaphor, it risks (i) epistemic extractivism—privileging algorithmic abstraction over situated indigenous knowledge; (ii) reframing relational governance as managerial control; and (iii) erasure of non-hierarchical, plural authority structures [30,33,43]. The CEH explicitly mitigates these risks. First, S3 is reframed as "ecosystem care" rather than command-and-control: federated learning ensures that community data are never extracted, and audit channels (S3*) are designed for collective learning rather than surveillance. Second, S4 operates as a hybrid intelligence layer that couples AIoT analytics with traditional ecological knowledge feeding via community observatories and indigenous calendars. Third, S5 is articulated as pluriversal governance: indigenous "Planes de Vida" and Afro-Colombian community councils are recognized as legitimate co-authors of systemic identity, not as objects to be aggregated. Operationally, this is supported by a power-aware diagnostic loop [43] that maps visible, hidden, and invisible power asymmetries along the Caribbean Mining Corridor before any technological deployment. The CEH thus reads VSM through a power-relations lens, treating cybernetic structure as scaffolding for, rather than substitute for, plural governance practices.

7.2. Novelty Differentiation from Prior VSM-Sustainability Work

To make the incremental contribution explicit and avoid overstating novelty, Table 4 summarizes how the CEH builds on, and differs from, prior VSM-sustainability work [21,30,33].

Table 4. CEH-specific contributions relative to prior VSM-sustainability work.

System	Prior VSM-Sustainability (Illustrative)	CEH-Specific Contribution
S1	Social/operational units, community cooperatives [30].	AIoT nodes with edge inference and TinyML in extractive territories.
S2	Coordination protocols, social audits [21].	Blockchain smart contracts with auditable rule-based interactions.
S3	Internal control, social-audit governance [33].	Federated-learning-based privacy-gradient sharing as data-sovereignty layer.
S4	Human foresight, scenario planning [30].	AIoT/EWS algedonic signals plus digital twins for event-horizon decoupling.
S5	Normative discourse on values [7].	Justice hardcoded via blockchain incentive contracts and pluriversal identity layer.
H1–H3	Implicit maturity intuitions in case studies.	Explicit four-dimension rubric with quantifiable proxies and retrospective scoring.

8. Governance Redesign Implications

Ison et al. (2014) establish that addressing wicked socio-ecological problems requires moving beyond static policy reform toward the systemic institutionalization of social learning and adaptive governance [11]. Subsequent studies expand this perspective by demonstrating that such transformative capacities demand a structural reconfiguration of historical institutional layering, particularly in territories constrained by entrenched power dynamics [12]. Consequently, the Cybernetic Environmental Hub (CEH) model implies not merely an incremental adjustment but a fundamental redesign of governance architectures in the Global South, shifting them from bureaucratic, reactive paradigms toward cybernetic, justice-embedded systems capable of sustaining long-term viability [13].

8.1. Institutional Reconfiguration: Adjusting Systems 2–4

The most persistent weaknesses in climate and energy governance in the Global South are not operational (System 1) but meta-systemic. Local communities often demonstrate strong collaborative initiative, yet their coordination, monitoring, and anticipatory intelligence remain fragile or entirely informal [45].

To overcome these limitations, the CEH framework necessitates a formal reconfiguration of Systems 2, 3, and 4. Figure 13 illustrates how environmental hubs can restructure governance architectures. At the coordination level (System 2), redesign requires transitioning from hierarchical intervention to agile, continuous feedback protocols that proactively manage shared resources—such as microgrids and water basins—damping oscillations before they escalate into crises [30].

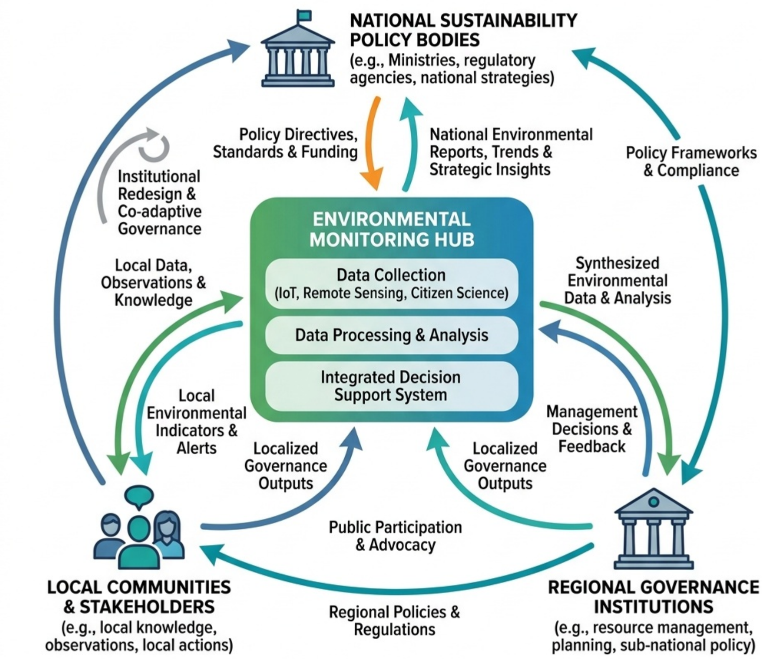

Figure 13. Governance redesign pathways for Cybernetic Environmental Hubs across Systems 2–4.

Similarly, oversight mechanisms (System 3) must be fundamentally transformed. Rather than functioning as external audit bureaucracies focused on punitive compliance, System 3 must evolve into an internal optimization organ. This requires embedding direct, sporadic verification channels (System 3*) capable of validating operational cohesion and fostering collective learning without suppressing local autonomy [45]. Furthermore, institutionalizing systemic reflexivity demands a robust predictive intelligence layer (System 4). Strategic planning must shift from static, donor-driven policy cycles toward continuous environmental scanning and digital twin modeling, enabling institutions to anticipate climate risks and adapt proactively [14]. This dynamic interplay between internal optimization and external foresight solidifies the "Homeostat of Adaptation," transitioning institutions from reactive bureaucracies into learning systems capable of strategic self-transformation [21,22].

8.2. Digital Infrastructure as Governance Backbone

In this redesigned architecture, digital infrastructure functions not as a peripheral support tool but as the structural backbone of organizational cybernetics. The integration of AIoT, big data, and edge computing constitutes an exercise in "variety engineering." By acting as structural amplifiers and attenuators, edge devices enable local operational units to process vast amounts of environmental complexity, thus acquiring the requisite variety needed to operate autonomously under high turbulence [42].

To address institutional distrust and limit digital extractivism, the CEH combines Federated Learning (FL) with blockchain-based smart contracts: FL keeps raw datasets localized within communities, while smart contracts support transparent and auditable incentive allocation [17,18,20]. In the same layer, Early Warning Systems (EWSs) are wired as algedonic signals so that breaches of essential sustainability variables (EVSs) trigger coordinated responses without passing through bureaucratic bottlenecks [19].

8.3. Scaling Environmental Hubs in the Global South

Finally, the structural reconfiguration proposed by the CEH model redefines how governance scales. Unlike conventional "one-size-fits-all" development models, CEHs scale fractally through the recursive principles of the VSM. The exact same functional design (Systems 1–5) operates consistently at the level of a local energy cooperative, a regional innovation ecosystem, or a national transition platform, preserving lower-level autonomy while ensuring higher-level cohesion [10].

This fractal scalability provides the institutional "plumbing" desperately needed by macro-scale financing frameworks, such as Just Energy Transition Partnerships (JETPs), which frequently suffer from opaque financial flows and high transaction costs [1,15]. By embedding auditable blockchain-based allocation mechanisms and structured coordination layers at meso and micro levels, CEHs drastically reduce political fragmentation. Climate finance thus becomes transparent, traceable, and distributively accountable, directly addressing the core vulnerabilities of contemporary multi-level transition initiatives [3]. By deploying CEHs, Global South territories can leapfrog traditional, slow bureaucratic modernization pathways, fostering endogenous development trajectories rooted in local identity and ecological stewardship [5,12]. Ultimately, this redesign transforms climate governance from fragmented administration into a viable, digitally integrated architecture capable of sustaining structural justice under profound socio-ecological turbulence.

9. Theoretical Contributions

This article advances theoretical debates at the intersection of organizational cybernetics, sustainability governance, energy transition theory, and climate justice. Lederer et al. (2025) establish that evaluating and governing profound socio-ecological shifts requires frameworks that move beyond descriptive complexity toward normative, prescriptive institutional redesign [10]. A cybernetic approach can complement this agenda by enriching narrative accounts of transitions with structured, systems-level design heuristics [12,21]. On this basis, the Cybernetic Environmental Hub (CEH) is offered as a candidate socio-technical architecture that contributes to the literature across four theoretical domains, aiming to position organizational cybernetics as a promising resource for emancipatory governance in the Global South, subject to further comparative validation [30].

9.1. Advancing the VSM in Sustainability Governance

Traditionally, the Viable System Model (VSM) has been applied primarily within corporate and organizational contexts. Espinosa (2022) establishes the theoretical extension of organizational cybernetics to the governance of socio-ecological systems and common-pool resources [30]. This article enriches that extension by integrating a "power-aware VSM," demonstrating how cybernetics must diagnose visible, hidden, and invisible power structures to prevent the co-optation of environmental governance [43]. Furthermore, whereas contemporary climate governance literature often suffers from theoretical fragmentation, the CEH model articulates deductive first-principle rules that guarantee structural viability under extreme complexity [14]. Therefore, by embedding adaptive coordination into the metasystem, the CEH provides the structural architecture necessary to balance local community autonomy with global ecological coherence [45].

9.2. Integrating Cybernetics with Energy Transition Theory

Energy transition scholarship has significantly advanced the understanding of niche innovation and regime destabilization, yet it often remains largely descriptive. Orr and Burch (2025) note that frameworks such as Transition Management effectively nurture innovation but lack the prescriptive mechanics to restructure entire institutional regimes [12]. To address this, the CEH model specifies exactly how Systems 1 through 5 must be reconfigured to absorb the variety introduced by climate and technological disruptions, treating digital infrastructures (AIoT, edge computing) as intrinsic variety amplifiers [10,19]. By reconceptualizing Early Warning Systems (EWSs) as algedonic signals that bypass slow hierarchies to induce proactive metasystemic learning, this framework firmly embeds anticipatory adaptation directly into transition theory [14].

9.3. Embedding Climate Justice Structurally

Perhaps the most significant theoretical contribution of this article is the structural embedding of climate justice within the cybernetic governance architecture. Csanadi and Helmeci (2025) highlight that in many international climate finance mechanisms, such as Just Energy Transition Partnerships (JETPs), justice remains peripheral—an outcome to be negotiated rather than a structural prerequisite [15]. In contrast, the CEH model hardcodes justice within System 5, elevating distributive and restorative equity from policy rhetoric to cybernetic necessity [7]. This is further operationalized through the concept of algorithmic distributive justice: integrating Federated Learning and blockchain-based smart contracts protects data sovereignty and mitigates risks of digital colonialism in the Global South [17,18]. Thus, justice is no longer external to governance but is deeply embedded in the socio-technical code of the system [20].

9.4. Proposing Maturity-Based Territorial Modeling

Finally, the article introduces a methodological and theoretical innovation through the Territorial Maturity Model (H1–H3). Orr and Burch (2025) establish that territorial evolution must be defined by systemic reflexivity and internal variety management, rather than relying exclusively on economic output or technology penetration [12]. Building on cybernetic learning theory, this model conceptualizes development as a progression from single-loop operational adjustments to deep institutional reinvention [21,33]. The Territorial Maturity Assessment Matrix provides a novel heuristic tool for diagnosing “variety gaps” across technological, institutional, and justice dimensions. In doing so, it bridges theoretical abstraction with actionable diagnostics, reframing regional development as a recursive path-dependent trajectory [14].

Collectively, these theoretical contributions reposition organizational cybernetics as a foundational, prescriptive science for sustainability governance in the Anthropocene, capable of guiding just energy transitions in structurally fragile yet innovation-rich territories of the Global South.

10. Policy Implications

Jain and Bustami (2025) establish that public policy for energy transitions must shift from regulating isolated actor behavior through hierarchical command-and-control to engineering the systemic conditions that enable socio-technical viability [1]. Subsequent evaluations of multi-level financing mechanisms expand this perspective, demonstrating that successful policy implementation requires structurally empowering local communities rather than merely imposing top-down decarbonization targets [2,15]. Consequently, the literature converges on the premise that achieving structural justice necessitates translating theoretical transition goals into actionable, digitally supported, and participatory governance mandates [4].

The Cybernetic Environmental Hub (CEH) framework operationalizes this paradigm shift by providing specific guidelines for policymakers, state agencies, and international financiers. To prevent speculative policy recommendations, this framework deliberately defines the concrete actors, legal instruments, and technological mechanisms required to enact systemic governance. The policy implementation architecture derived from the model is presented in Figure 14. This architecture organizes policy interventions into four actionable domains: digital infrastructure investments, participatory governance design, open data mandates, and transition monitoring systems.

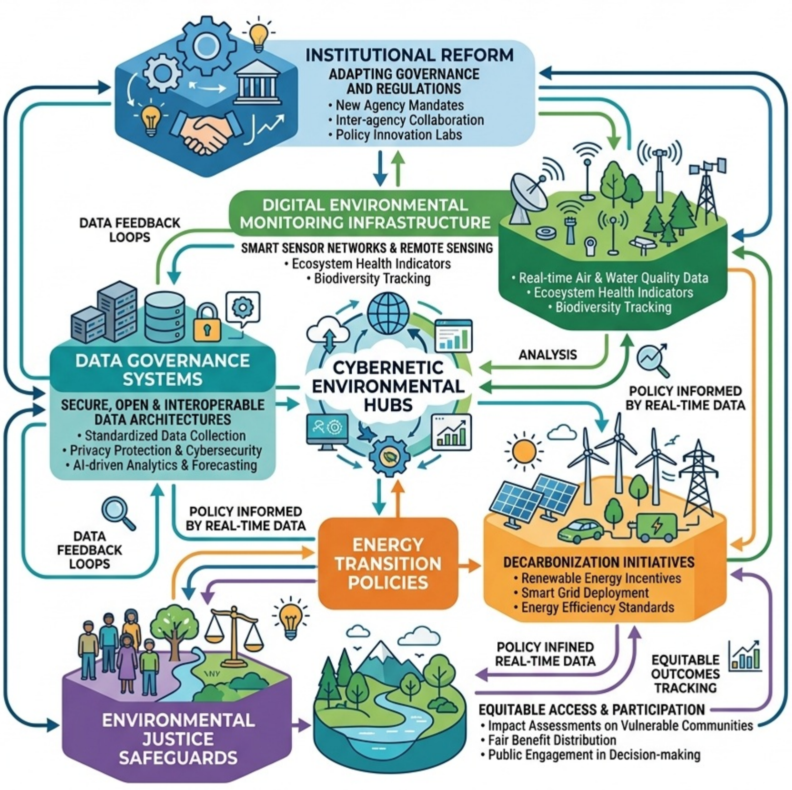

Figure 14. Policy implementation architecture for Cybernetic Environmental Hubs.

10.1. *Digital Infrastructure Investments*

Climate finance, particularly through Just Energy Transition Partnerships (JETPs), has traditionally prioritized heavy generation infrastructure. The CEH model suggests reorienting a significant portion of these funds toward the cyber-physical nervous system required for community autonomy [16]. Policy agendas should explicitly finance "variety amplifiers," such as edge AIoT networks and municipal digital twins, so local operational units can autonomously manage renewable intermittency and climate volatility [14]. Governments should also incentivize decentralized trust infrastructures via regulatory sandboxes that permit blockchain smart contracts for transparent resource distribution and lower transaction costs [17,20].

10.2. *Participatory Governance Design*

Just transitions cannot be imposed hierarchically; public policy must institutionalize co-creation to prevent elite capture. State agencies should formally finance "social learning spaces" and Living Labs, shifting from technocratic solution imposition to continuous socio-ecological co-production [11]. Crucially, energy transition regulations must mandate the adoption of "power-aware" governance principles. This requires systematic audits of invisible power asymmetries to ensure marginalized communities exercise genuine influence over System 5 (identity and purpose) [43]. Additionally, ministries must promulgate legal frameworks that grant formal operational autonomy (System 1) to community-based structures, such as rural energy cooperatives, preventing bureaucratic suffocation [30,45].

10.3. Open Data Mandates

Policy must resolve the inherent tension between global transparency and local data sovereignty. Governments should mandate that macro-level environmental datasets comply strictly with FAIR principles (Findable, Accessible, Interoperable, Reusable), strengthening regional Spatial Data Infrastructures (SDI) to enable citizen science and enhance institutional legitimacy [14]. Simultaneously, national innovation policies must require privacy-by-design architectures, such as Federated Learning, to prevent digital extractivism. This ensures that raw physical-social data remains localized within communities [18]. Financial regulations should further enable smart contracts to guarantee equitable, immutable compensation for communities contributing critical environmental data or surplus renewable energy to the grid [20].

10.4. Transition Monitoring Systems

Traditional monitoring relies on retrospective reporting, whereas the CEH framework requires real-time, cybernetic oversight. Policy guidelines must transform Early Warning Systems (EWSs) into legally mandated "algedonic signals"—automated alerts that bypass bureaucratic delays to trigger inter-institutional emergency responses when essential sustainability variables are breached [19]. Furthermore, monitoring mechanisms for Nationally Determined Contributions (NDCs) must expand beyond carbon mitigation metrics to include mandatory indicators for distributive justice, labor protection, and social resilience [46]. Finally, state planning agencies should adopt the proposed H1–H3 territorial maturity model to continuously diagnose systemic reflexivity. By diagnosing variety gaps, institutions can tailor digital investments and capacity-building to the specific evolutionary trajectory of each territory, abandoning technocratic one-size-fits-all solutions [12,21].

Ultimately, the CEH framework demands a regulatory paradigm shift: public policy must transition from reactive supervision to proactive systemic engineering, aligning climate governance with the autonomy, viability, and structural justice required for successful energy transitions in the Global South.

10.5. Anchoring Policy in the Colombian Context

To avoid generic prescription, the four policy domains above are mapped to existing Colombian instruments, named actors, indicative timelines and known veto points. Digital infrastructure investments can be channelled through the Sistema General de Regalías (SGR) under MinCiencias-led programmatic calls (e.g., the Call 31 mechanism that funds project BPIN 2023000100072), with regulatory sandboxes for blockchain-based smart contracts under Banco de la República and Superintendencia Financiera oversight; the principal veto point is municipal capacity to formulate and execute SGR projects. Participatory governance design can be operationalized via Corpoguajira, Corpocesar and Corpamag (CARs), in coordination with MinAmbiente, indigenous authorities under ILO Convention 169, and Afro-Colombian community councils, with citizen oversight committees (veedurías) institutionalized at the municipal level; the binding constraint is elite capture in mining-dependent municipal economies. Open data mandates can build on Constitutional Court ruling T-614/2019 (right to environmental information), Resolución 2254/2017 ($PM_{2.5}$/PM_{10} thresholds), and ANLA's Auto 5755 environmental compliance procedures, with FAIR-aligned APIs interoperable with IDEAM/SISAIRE; the relevant veto point is jurisdictional overlap between national and regional environmental authorities. Transition monitoring systems can extend Colombia's NDC reporting to include distributive-justice and digital-rights indicators, with a pilot phase targeted for 2027 in the Caribbean Mining Corridor before scale-up. The well-documented constraints—internet penetration as low as 6.68% in some Caribbean municipalities and structural mining dependence—reinforce the importance of the low-tech fallback layer (Section 4) and of the H1–H3 rubric (Table 3) for sequencing investments realistically.

11. Limitations

While the Cybernetic Environmental Hub (CEH) framework advances a structurally integrated model for just energy transition governance, its empirical and methodological boundaries must be acknowledged. These limitations do not undermine the conceptual contribution of the architecture; rather, they delineate a rigorous agenda for future testing.

First, the empirical validation of the CEH model is currently grounded in a single territorial context—the Caribbean Mining Corridor. Fathi et al. (2025) note that a broader limitation in contemporary Viable System Model (VSM) research is the scarcity of extensive longitudinal field validation [19]. Other scholars similarly emphasize that applying cybernetic frameworks to highly specific socio-ecological governance systems allows only for cautious extrapolation [47–50]. Therefore, while this case provides a high-complexity setting for testing cybernetic redesign, replication across diverse geographies is required to confirm the framework's structural resilience and scalability.

Second, the methodological core relies on participatory datasets, presenting inherent constraints. Espinosa (2022) establishes that translating abstract cybernetic constructs—such as recursion and requisite variety—into accessible language for rural or indigenous communities presents significant facilitation challenges [30]. Subsequent studies expand on this, warning that without advanced ethnographic heuristics, participatory coding risks overlooking subtle traditional self-organizing mechanisms [33]. Consequently, the qualitative nature of the Banco de Retos I+D+i introduces potential interpretive bias, highlighting the need to triangulate these narratives with quantitative environmental performance metrics in future iterations [19].

Finally, the generalization of the CEH model faces structural institutional barriers. Liu (2026) argues that comparative multiscale validation is necessary before cybernetic frameworks can transition from descriptive proposals to normative governance standards [14]. Furthermore, territorial transformation is inherently path-dependent; adaptive capacity evolves historically through institutional layering and socio-political contingencies [12]. Thus, the CEH framework cannot function as a simple "plug-and-play" solution, particularly given the low systems literacy and organizational resistance frequently found in Global South bureaucracies [19]. Its implementation requires deep institutional adaptation aligned with pre-existing power structures and local socio-ecological dynamics, while also accounting for community-based transition pathways, solidarity-economy institutions, and fossil-fuel subsidy lock-ins [51–53].

For clarity, the three limitations identified above—(L1) single-site empirical grounding, (L2) qualitative–interpretive bias of participatory diagnostics, and (L3) institutional path-dependence and resistance—are used as the explicit organizing principle of the future research agenda presented in Section 12.

Beyond these methodological limitations, two design-level risks inherent to the CEH itself must be acknowledged. (L4) Algorithmic exclusion and data colonialism. Edge-AI inference models trained predominantly on external or non-representative datasets risk encoding biases that reproduce technocratic exclusion and override situated community knowledge. The CEH mitigates this through federated learning (no raw data leaves the community), TOPSIS/CRITIC-weighted node siting that incorporates social-vulnerability variables, and Shapley-based incentive mechanisms that compensate communities for their contributions; nevertheless, the residual risk warrants periodic algorithmic audits and open-source publication of model cards. (L5) Ontological mismatch between VSM cohesion and plural governance practices. The VSM's emphasis on systemic cohesion can conflict with the non-hierarchical, relational governance practices of Afro-Colombian and indigenous communities in the Caribbean Mining Corridor. We address this through a "plural VSM" adaptation in which S5 is co-authored with traditional authorities and "Planes de Vida" are recognized as legitimate identity constructs, but we acknowledge that this adaptation is provisional and requires longitudinal ethnographic validation.

12. Future Research

The future research agenda outlined below is designed to address, one-to-one, the three main limitations identified in Section 11: single-site empirical grounding, qualitative–interpretive bias, and institutional path-dependence of the framework. Rather than a generic roadmap, each trajectory responds to a specific weakness of the current study.

Fathi et al. (2025) establish that advancing the Viable System Model (VSM) from a diagnostic tool into a precision institutional engineering discipline requires moving beyond qualitative single-case applications [19]. Subsequent studies have expanded this perspective, demonstrating that evaluating territorial transformative capacities demands longitudinal testing across diverse socio-ecological contexts [12]. In line with Limitation 1 (single-site validation), the literature converges on the necessity of advancing from descriptive institutional frameworks toward robust, cyber-physical governance simulation and quantitative cross-regional validation [10].

To realize this transition, future research must converge along four complementary trajectories: cross-regional comparison, quantitative testing, computational simulation, and digital twin integration. Figure 15 outlines a research roadmap for advancing cybernetic environmental governance.

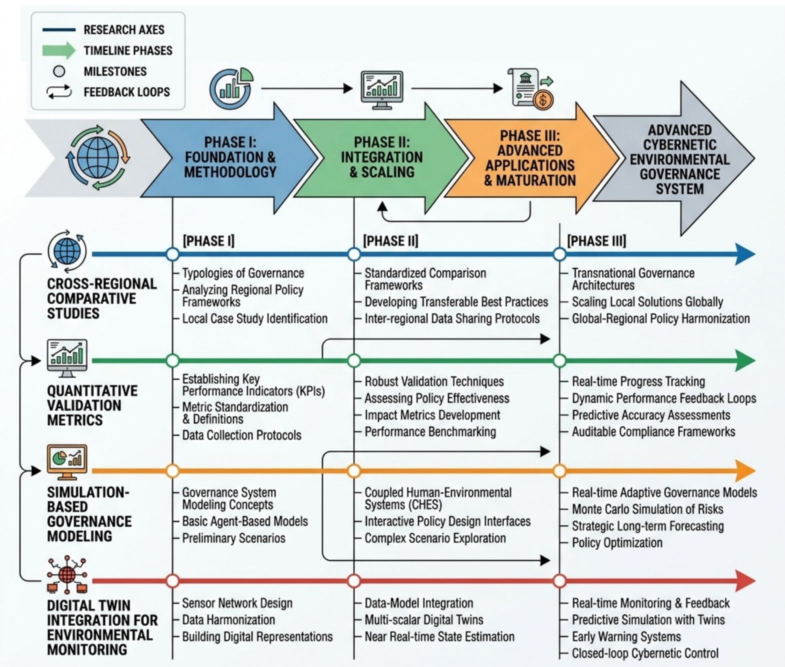

Figure 15. Research roadmap for advancing cybernetic environmental governance.

First, addressing Limitation 1 (single-site grounding), cross-regional comparative studies are needed to assess the diagnostic robustness of the Cybernetic Environmental Hub (CEH) architecture under differentiated political regimes, environmental turbulence, and digital infrastructure baselines [47]. Second, responding to Limitation 2 (qualitative–interpretive bias of participatory diagnostics), future scholarship should combine the qualitative coding used here with quantitative validation metrics—transaction cost reduction, variance in resource allocation conflicts, and response times to environmental shocks—so that participatory narratives can be triangulated with measurable viability indicators [19].

Third, simulation-based governance modeling using System Dynamics (SD) and Agent-Based Modeling (ABM) directly addresses Limitation 3 (path-dependence and institutional resistance): it allows researchers to computationally stress-test recursive coordination structures under different historical institutional trajectories, climate shocks and energy price volatility, without exposing physical communities to real-world risks [19]. Fourth, integrating digital twins into the governance architecture tackles the intersection of Limitations 1 and 3, providing continuous sensory-analytical engines for the real-time anticipatory optimization of distributed renewable systems and for longitudinal comparative monitoring across territories [14].

By pursuing this limitation-anchored roadmap, future research can gradually upgrade organizational cybernetics from a diagnostic framework toward a scalable design science for viable, justice-centered socio-technical systems across the Global South.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su18157764/s1, Table S1: Illustrative mapping from community-reported challenges to codes, clusters, and VSM subsystems; Table S2: Territorial Maturity Assessment Matrix.

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