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A MULTI-LAYER BIOMIMETIC SOCIO-TECHNICAL ARCHITECTURE FOR PHOTOVOLTAIC AND AGRIVOLTAIC SYSTEMS: INTEGRATING COMPETENCE INFRASTRUCTURE AND COMMUNITY CO-DEVELOPMENT IN THE GLOBAL SOUTH

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Abstract
Photovoltaic (PV) and agrivoltaic systems are increasingly deployed to address energy access, land-use efficiency, and climate resilience challenges across Africa and the Global South. However, long-term system performance frequently remains constrained by workforce capability gaps, weak institutional integration, limited community participation, and fragmented socio-technical design approaches. This study proposes a multi-layer biomimetic socio-technical architecture that integrates energy systems, competence infrastructure, community co-development, biomimetic intelligence, and resilience mechanisms within a unified engineering framework. Rather than treating these dimensions as external influences, the architecture conceptualizes them as interacting subsystems within an adaptive and evolving renewable energy ecosystem. Competence infrastructure is formalized as an endogenous system variable influencing deployment capability, while cross-layer interactions capture feedback, coordination, and adaptation across technical, ecological, and social domains. The resulting architecture models PV and agrivoltaic systems as nonlinear, time-evolving socio-technical systems in which overall performance emerges from subsystem interactions rather than isolated technical optimization. The framework provides a scalable basis for renewable energy deployment planning, environmental management, policy design, and long-term system sustainability in resource-constrained environments and developing economies.

Keywords: *Agrivoltaic Systems, Biomimetic Socio-Technical Architecture, Competence Infrastructure, Community Co-Development, Photovoltaic Systems, Renewable Energy Transitions, Resilient Energy Systems, Environmental Management*

Introduction

Engineering systems are traditionally described in terms of physical components and technical configurations. In practice, however, their long-term performance depends equally on the human, institutional, and environmental systems within which they operate. This is particularly evident in photovoltaic (PV) and agrivoltaic systems, which

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increasingly occupy dual roles as energy infrastructure and environmental management interventions, influencing land-use efficiency, ecosystem interactions, agricultural productivity, and climate resilience. Their successful deployment therefore requires engineering approaches capable of integrating technological performance with ecological adaptation and socio-environmental dynamics (Weselek *et al.*, 2021; Barron-Gafford *et al*., 2019; Geels, 2019; Lesala and Mukumba, 2025).

Renewable energy transitions are increasingly recognized not merely as technological transformations but as environmental management challenges involving land use, resource governance, community participation, and the resilience of socio-ecological systems. In developing economies, the long-term sustainability of decentralized energy systems depends on the successful integration of technical infrastructure with environmental stewardship and local institutional capacity.

This challenge is especially pronounced across Sub-Saharan Africa and Southeast Asia, where the expansion of distributed renewable energy systems is constrained not only by technological limitations but also by workforce capability gaps, institutional fragmentation, and limited integration of community-level dynamics. These constraints intersect with persistent energy access deficits that continue to undermine socio-economic development. In Nigeria, for example, chronic electricity shortages persist despite abundant solar resources. Decentralized PV systems therefore continue to emerge as viable pathways for electrification, while agrivoltaic systems are increasingly positioned as integrated solutions for energy access, agricultural productivity, climate adaptation, and environmental sustainability through dual land-use optimization and mitigation of land-use conflicts.

Competence, Governance and Deployment Challenges

The long-term performance and scalability of PV and agrivoltaic systems depend not only on technological efficiency but also on their alignment with local competence systems, governance structures, and community dynamics operating across multiple system layers. This is particularly evident in distributed energy systems where project success frequently depends on the availability of skilled personnel, maintenance ecosystems, institutional coordination, and locally embedded support structures.

Recent deployment trends suggest that the principal constraints affecting renewable energy systems are no longer purely technological or financial. Increasingly, limitations arise from implementation capacity deficits, workforce preparedness, weak maintenance systems, insufficient knowledge transfer, and low public awareness. These conditions are especially visible in rapidly expanding renewable energy markets across Nigeria and other parts of the Global South, where technical solutions are increasingly available but long-term deployment performance remains uneven.

Distributed solar systems therefore operate within complex socio-technical ecosystems involving engineers, communities, institutions, policymakers, and environmental constraints. The absence of integrated system architectures capable of coordinating these interacting domains frequently results in maintenance failures, weak local ownership, limited adaptive capacity, and reduced deployment sustainability.

Fragmentation across Existing Knowledge Domains

Despite increasing interest in renewable energy deployment systems, existing research remains predominantly optimization-driven, emphasizing energy yield, crop response, microclimatic interactions, and techno-economic performance while insufficiently addressing the broader socio-technical conditions governing sustained system functionality.

Biomimetic research advances principles of adaptation, resilience, redundancy, and feedback derived from natural systems but has not been systematically operationalized as a systems design logic for renewable energy infrastructure architectures. Agrivoltaic research provides detailed technical and environmental analyses but only partially incorporates governance structures, competence generation processes, and social integration mechanisms. Community energy studies emphasize participation and local ownership yet frequently position communities as stakeholders rather than as active agents of community co-development and co-engineering. Similarly, workforce development research identifies capability deficits as critical deployment constraints but rarely embeds competence infrastructure directly within engineering system design.

Consequently, a structural disconnection persists between technological systems, community dynamics, environmental management processes, and competence generation mechanisms. Existing frameworks therefore remain limited in their ability to explain the interactions among technical infrastructure, adaptive capability, governance systems, and local socio-cultural environments that collectively determine long-term renewable energy deployment performance.

Research Gap and Contribution

This study addresses this systemic gap by advancing a multi-layer biomimetic socio-technical architecture for PV and agrivoltaic systems that explicitly integrates competence infrastructure and community co-development as co-equal structural components within a unified engineering system representation.

The proposed architecture conceptualizes renewable energy systems as adaptive and layered socio-technical ecosystems in which technological, ecological, institutional, and human capability domains are dynamically coupled. Biomimetic intelligence is introduced as a foundational systems logic through which adaptation, resilience, and feedback mechanisms are embedded across architectural layers. Competence infrastructure is formalized as an endogenous engineering subsystem governing deployment capability, maintenance readiness, and long-term system reliability, while community co-development is positioned as a generative mechanism through which local knowledge, participation, governance, and ownership become integrated components of system evolution.

Building upon prior work that established and empirically validated competence infrastructure constructs, this study extends the analysis toward system-level integration by defining cross-layer interactions, feedback pathways, and environmental interfaces connecting competence generation, technological performance, and community systems. In doing so, it reconceptualizes PV and agrivoltaic systems as adaptive socio-technical energy ecosystems rather than isolated technological artefacts.

The study contributes to renewable energy systems research in several ways. First, it develops a system-level architecture that integrates technical, ecological, institutional, and social dimensions rather than treating them as separate domains. Second, it embeds competence infrastructure directly within engineering system design, making workforce capability an endogenous component of system performance. Third, the framework is designed for practical application in African and ASEAN contexts where decentralized renewable energy systems operate under complex institutional, governance, capacity, and resource constraints that require locally embedded and socio-technically integrated deployment approaches (IRENA, 2024; Kuok *et al.*, 2024; Takal *et al.*, 2026). Finally, by incorporating community co-development, participation, governance, and social learning as intrinsic performance determinants, the architecture contributes to environmental design and management through the development of resilient, adaptive, and sustainable energy landscapes across the Global South.

The present study forms part of a broader research programme on competence infrastructure and socio-technical renewable energy systems. The preceding companion studies established competence infrastructure as an engineering systems construct and subsequently examined its role as a measurable determinant of photovoltaic deployment capability within community-based deployment contexts. To provide continuity between these foundational studies and the systems-level framework developed here, a companion communication consolidates the competence infrastructure construct into an independently defined systems engineering representation. Building upon that consolidated construct, the present study integrates competence infrastructure within a multi-layer biomimetic socio-technical architecture for photovoltaic and agrivoltaic systems, thereby extending the research programme from subsystem conceptualization and validation to whole-system architectural integration.

Methodology and Architectural Development Procedure

The proposed multi-layer biomimetic socio-technical architecture represents the integration stage of a broader research programme on renewable energy deployment systems in developing economies. Earlier stages of this programme involved conceptual development of competence infrastructure constructs together with empirical investigations of workforce readiness, deployment capability, technical support structures, and renewable energy implementation constraints within photovoltaic deployment environments.

Accordingly, the present study adopts a systems engineering–based integrative research design that combines empirical insights from earlier investigations with contemporary knowledge on biomimicry, agrivoltaics, socio-technical transitions, and community energy systems to develop a generalized renewable energy architecture. Rather than emerging solely from conceptual abstraction, the architecture is derived from cumulative evidence generated through competence modelling, deployment analysis, and capability assessment undertaken within the broader doctoral research programmes (Chris-Abey, 2022).

Architecture Development Procedure

Architecture development followed a four-stage systems engineering procedure designed to ensure reproducibility and methodological traceability.

Stage 1: Conceptual synthesis and evidence integration. Empirical observations and literature evidence were synthesized to identify recurring determinants of renewable energy deployment performance. Four knowledge domains informed this process: biomimicry, agrivoltaic systems, socio-technical systems, and competence infrastructure.

Stage 2: Functional decomposition and system definition. The renewable energy system was defined as a socio-technical ecosystem comprising photovoltaic or agrivoltaic infrastructure embedded within community environments and supported by competence development mechanisms. Functional decomposition identified five recurring system functions: ecological intelligence, energy generation, competence generation, community co-development, and resilience feedback.

Stage 3: Subsystem identification and interaction modelling. The identified functions were translated into interacting architectural layers representing biomimetic intelligence, technical energy systems, competence infrastructure, community co-development, and resilience mechanisms. Interaction modelling established the principal system flows consisting of energy flow, competence flow, and community feedback flow.

Stage 4: Architecture abstraction and generalization. The resulting architecture was abstracted into a modular representation capable of adaptation across different socio-economic, institutional, and environmental contexts, particularly within developing regions.

Validation Logic and Methodological Contribution

The methodological contribution of this study lies in extending systems engineering principles to incorporate ecological, institutional, and competence dimensions within a unified architecture. The credibility of the framework is supported through structural coherence, theoretical consistency, and alignment with empirical findings from preceding investigations and contemporary socio-technical systems literature.

The architecture should therefore be interpreted as an evidence-informed systems representation rather than a purely conceptual construct. Its modular structure preserves sufficient flexibility for future calibration, quantitative implementation, and empirical validation using operational deployment datasets.

Operationalization and Implementation Pathway

To ensure applicability and reproducibility, the architecture is operationalized using measurable system variables corresponding to the formal system equations presented in Eq. (1) – (10).

- *Competence Infrastructure (C):* measured using training metrics, certification levels, diagnostic performance, and feedback learning rates.
- *Biomimetic Intelligence (B):* represented through adaptive design features, ecological integration, and environmental responsiveness.
- *Technical System Performance (T_{sys}):* measured through photovoltaic

efficiency, system uptime, and maintenance reliability.

- *Community Co-Development (D):* represented using participation indices, governance effectiveness, and local ownership indicators.
- *Competence Infrastructure Layer (I):* generates competence output through training, diagnostics, simulation, and feedback mechanisms.
- *Resilience and Feedback (R):* measured using recovery rates, adaptation frequency, and performance stability under disturbance conditions.

Implementation follows three operational stages:

1. *System Mapping:* identification and quantification of subsystem variables within a deployment context.
2. *Model Calibration:* estimation of coefficients - α (alpha), β (beta), γ (gamma), δ (delta), λ (lambda), ϕ (phi), and Ω (omega) - using empirical observations or context-specific proxies.

Scenario Analysis: evaluation of system performance and deployment risk under alternative competence, governance, and environmental conditions.

This operational structure enables application of the framework in both data-rich and data-constrained environments, supporting deployment planning, policy analysis, and future empirical validation across decentralized renewable energy systems.

Biomimetic Socio-Technical Architecture for Photovoltaic and Agrivoltaic Systems

To address the identified systemic gaps, a biomimetic socio-technical architecture is developed in which photovoltaic and agrivoltaic systems are represented as adaptive engineering systems operating across coupled ecological, technological, and community domains. The architecture consists of five interacting layers: biomimetic intelligence (B), energy systems (E_{sys}), community co-development (D), competence infrastructure (I), and resilience and feedback (R). Functional mappings are assumed continuous and bounded, with subsystem interactions defined according to their engineering roles.

The integrated socio-technical ecosystem system (S_{eco}), is represented as:

$$S_{eco} = (L, A, E_{env}, C, X) \qquad (1)$$

where $L = [L_1, L_2, L_3, L_4, L_5]$ denotes the five layers, A represents system agents including engineering and other technical personnel, communities, firms, institutions, and other stakeholders participating in system operation, governance, and evolution; E_{env} denotes environmental conditions including climatic, policy, economic and land-use factors, C is competence output, and X represents cross-layer interactions defined in Eq. (9).

Community co-development captures participatory governance, local ownership, institutional coordination, and decision processes using indicators such as participation rates, institutional trust, and management effectiveness. These variables influence both deployment performance and long-term sustainability. System evolution is expressed as:

$$S_{eco}(t+1) = F(S_{eco}(t), A(t), E_{env}(t)) \qquad (2)$$

where F defines subsystem evolution through internal interactions, agent actions, and environmental influences. Eq. (1) defines structure while Eq. (2) defines behaviour, establishing the architecture as a nonlinear and adaptive socio-technical system.

The formulation preserves competence infrastructure as an endogenous engineering variable consistent with earlier studies, allowing direct integration of subsystem and empirical models within a unified architecture. Inputs include solar resources, land, participation and competence requirements, while outputs include energy generation, agricultural productivity and sustained functionality.

Conceptual synthesis and knowledge integration

The architecture was developed through structured synthesis of four knowledge domains: biomimicry, agrivoltaic energy systems, socio-technical systems theory, and competence infrastructure. These domains were integrated according to their functional relevance to renewable energy system performance and sustainability.

Biomimicry contributed principles of adaptation, redundancy, and feedback regulation (Hayes *et al.*, 2020; Ilieva *et al.*, 2022; AlAli *et al.*, 2023; Abey-Fashae, 2024). Agrivoltaic systems informed the physical infrastructure and agro-energy coupling dimensions, while socio-technical systems theory introduced governance and community participation dynamics (Sovacool *et al.*, 2019). Competence infrastructure provided the capability generation subsystem underpinning workforce readiness and long-term system sustainability (Fred *et al.*, 2024). The resulting synthesis informed subsystem identification and architecture development consistent with interdisciplinary systems engineering approaches to energy transitions (Geels, 2019).

Biomimetic Intelligence Subsystem

Biomimetic intelligence provides the adaptive control logic governing subsystem interaction and evolution. It operationalizes four principles: adaptation, redundancy, symbiosis, and distributed functionality (Hayes *et al.*, 2020).

Adaptation enables responses to climatic and operational variability; redundancy reduces vulnerability to component failure; symbiosis strengthens agro-energy interactions; and distributed functionality decentralizes operation to improve robustness and scalability. Together these principles embed ecological intelligence directly within engineering system behaviour.

Energy System Subsystem

The energy subsystem constitutes the physical core of the architecture, integrating photovoltaic and agrivoltaic systems through energy conversion, agro-energy coupling and land-use optimization.

Photovoltaic modules generate electricity while agrivoltaic configurations regulate interactions among solar infrastructure, crops, temperature and soil moisture dynamics (Weselek *et al*., 2021; Elamri *et al*., 2018). Unlike conventional optimization models, system configuration is influenced by community governance and competence availability, linking technical performance with social and institutional conditions (Pascaris *et al*., 2021).

Community Co-Development Subsystem

Community co-development transforms participation from an external condition into an internal engineering function. The subsystem governs resource allocation, ownership structures, benefit-sharing arrangements and local decision-making processes. Community inputs influence site selection, land use and technology choices, while governance mechanisms coordinate interactions among communities, operators and institutions (Lesala and Mukumba, 2025; IRENA Coalition for Action, 2021). Integration with competence infrastructure enables effective participation, improves acceptance and reduces deployment risk.

Competence Infrastructure Subsystem

Competence infrastructure represents the principal innovation of the architecture by embedding workforce capability directly within system design. Consistent with earlier work, competence is defined as:

$$C = f(S,P,D,F) \qquad (3)$$

where simulation (S), procedural training (P), diagnostics (D), and feedback (F) generate competence output (C).

Its temporal evolution is expressed as:

$$C_i(t+1)=C_i(t)+\alpha S_i(t)+\beta Pi(t)+\gamma D_i(t)+\delta F\mathrm{i}(t) \qquad (4)$$

where α, β, γ, and δ are subsystem conversion coefficients.

The subsystem supports implementation, operation and maintenance through simulation, training, diagnostics and feedback reinforcement. It interacts directly with energy systems, community processes and resilience mechanisms, improving reliability and scalability, particularly in resource-constrained environments (IRENA, 2022; Fred *et al.*, 2024).

Resilience and Feedback Subsystem

The resilience subsystem provides adaptive regulation through monitoring, analysis and feedback control.

System resilience evolves according to:

$$R(t+1)=R(t)+\lambda\Psi(M(t),A_{dap}(t),C(t))$$
$$0 \le R(t) \le 1 \qquad (5)$$

where λ is the adaptation sensitivity coefficient governing system responsiveness, Ψ *(psi)*$(\cdot)$ represents the adaptive response mechanism through which monitoring outputs, adaptive interventions, and competence availability are translated into resilience improvements, $M(t)$ denotes monitoring outputs, $A_{dap}(t)$ represents adaptive actions, and $C(t)$ represents competence output.

Resilience emerges from the interaction between feedback and capability, enabling continuous adaptation to technical, environmental and social disturbances.

Subsystem Interaction and System Flows

Consistent with earlier studies, engineering deployment capability *(EDC)* remains a function of competence:

$$EDC = f(C) \qquad (6)$$

The integrated architecture extends this relationship to include system interactions:

$$EDC^* = f(C,B,T_{sys},D,R) \qquad (7)$$

where EDC^* is the engineering deployment capability ***within*** S (integrated socio-technical ecosystem) as previously defined, and B, T_{sys}, D, and R represent biomimetic intelligence, technical performance, community co-development, and resilience respectively.

Technical performance (T_{sys}) includes energy yield, performance ratio, uptime, and fault incidence. Competence directly influences these indicators through installation quality, maintenance efficiency and diagnostic capability.

Overall system performance is represented as:

$$P_{sys} = g(C,B,T_{sys},D,R) \qquad (8)$$

where $g(.)$ maps subsystem states into overall system performance, demonstrating that functionality emerges from coupled interactions rather than isolated subsystem behaviour.

To formalize integratability:

$$X = Int_{uv} \quad (9)$$

where X defines the interaction structure of the system; $u \neq v$; $Int_{uv} = \phi(L_u, L_v, C, E_{env}, A)$; and Int_{uv} denotes interaction strength between layers, u and v being indices representing any two different layers within the five-layer architecture, and $\phi(.)$ captures coordination, dependency and feedback relationships. Strong interactions promote integration while weak interactions generate fragmentation.

System functionality therefore emerges through three coupled flows: energy flow, knowledge and competence flow, and community feedback flow. These interactions link technology, governance and capability into a coherent deployment ecosystem.

Architecture Synthesis and System Representation

The resulting architecture conceptualizes photovoltaic and agrivoltaic systems as adaptive socio-technical ecosystems in which performance emerges from interactions among ecological intelligence, technological infrastructure, community processes and competence development.

Unlike conventional optimization models, the framework emphasizes interdependence, resilience and long-term sustainability. Its modular structure supports transferability across deployment contexts, particularly within Global South environments where interactions among technology, institutions and capability structures strongly influence renewable energy outcomes.

Discussion and Implications

The findings suggest that the long-term performance of photovoltaic and agrivoltaic systems depends not only on technical optimization but on also the socio-technical conditions supporting deployment, operation, and adaptation. Many systems perform well under controlled conditions but experience reliability challenges in operational environments where competence, governance, and maintenance ecosystems remain weak.

Addressing Socio-Technical Gaps in Photovoltaic and Agrivoltaic Systems

The proposed architecture addresses a persistent limitation in renewable energy design: the separation of technological infrastructure from the socio-technical conditions required for sustained functionality. Existing approaches remain largely optimization-driven, emphasizing energy yield, land-use efficiency, and techno-economic performance while underrepresenting governance, participation, and capability development (Weselek *et al*., 2021; Pascaris *et al*., 2021). Recent reviews similarly highlight inadequate integration across technical, ecological, and institutional domains, limiting scalability and resilience (Favi *et al*., 2024; Njema *et al*., 2025; Duran-Cabezas *et al*., 2025).

By integrating biomimetic intelligence, community co-development, and competence infrastructure directly within system architecture, performance becomes an emergent property of subsystem interactions rather than isolated component efficiency. This extends socio-technical systems theory by embedding social processes formally within engineering design (Geels, 2019; Jenkins *et al*., 2018).

Implications for Renewable Energy Deployment in the Global South

The architecture is particularly relevant to Nigeria and the Global South, where renewable energy deployment is constrained more by competence deficits and institutional fragmentation than by technological limitations (Fred *et al*., 2024; IRENA, 2022). By internalizing competence infrastructure, workforce capability becomes a system function rather than an external dependency.

Deployment risk is represented as:

$$DRM^* = 1 - \Omega(C,D,R) \qquad 0 \leq \Omega \leq 1 \qquad (10)$$

where *DRM** is deployment risk and *Ω* is a stabilization function increasing with competence *(C)*, community co-development (*D*), and resilience (*R*). Improvements in these variables reduce deployment risk through stronger coordination and adaptive capacity.

The generalized functions *f*, *g*, *ϕ*, and *Ω* permit implementation using empirical regression, system dynamics, or machine learning approaches depending on available data and deployment complexity.

Community co-development further improves deployment outcomes by embedding local actors directly within governance and operational processes, strengthening participation, ownership, and long-term sustainability (Hanke and Guyet, 2023; Shortall and Mengolini, 2025; Lesala and Mukumba, 2025).

Agrivoltaic integration additionally supports land-use optimization and strengthens responses to the water-energy-food nexus through coordinated interaction among ecological, technological, and social subsystems.

Conceptual Application Scenario

Consider a rural agrivoltaic deployment characterized by low initial competence infrastructure (*C*). Improvements in simulation (*S*) and procedural training (*P*) increase competence through Eq. (4), which subsequently improves engineering deployment capability through Eq. (6), strengthens resilience through Eq. (5), and reduces deployment risk through Eq. (10). The scenario illustrates how the framework can guide targeted interventions in training and system design.

Engineering and Policy Implications

The architecture advances a transition from static infrastructure models toward adaptive socio-technical systems. Conventional engineering approaches optimize infrastructure for predefined conditions, whereas the present framework models performance as a product of continuous subsystem interaction and feedback.

Biomimetic principles of adaptation, redundancy, symbiosis, and distributed functionality provide mechanisms for resilience under environmental and operational uncertainty (Hayes *et al*., 2020). Simultaneously, competence infrastructure extends engineering system boundaries to include workforce capability as a determinant of reliability and performance.

Policy implications are equally significant. Infrastructure deployment alone is insufficient for long-term sustainability if training systems, institutional arrangements, and governance structures remain weak (Jenkins *et al*., 2018; Sovacool *et al*., 2019). Embedding competence and participation within system architecture supports more resilient and equitable energy transitions while strengthening energy justice through local ownership and benefit sharing.

Contribution to Systems Theory and Future Research

The architecture bridges an important divide between socio-technical systems theory and engineering systems design. Socio-technical approaches often lack formal engineering representation, while engineering models frequently exclude social and institutional variables (Geels, 2019). The proposed framework integrates technological, ecological, governance, and competence subsystems within a single architecture, demonstrating that performance emerges from subsystem interactions rather than component optimization alone.

Several limitations remain. The architecture requires empirical validation across diverse deployment contexts, while quantitative modeling of subsystem interactions warrants further investigation using system dynamics, agent-based modeling, and simulation approaches. Future research should also explore mechanisms for embedding competence infrastructure within educational and institutional systems and evaluate implementation challenges associated with fragmented governance environments.

Conclusion

This study develops a biomimetic socio-technical architecture for photovoltaic and agrivoltaic systems that integrates technological infrastructure, competence development, community co-development, and ecological intelligence within a unified engineering framework.

Building on earlier work that formalized competence infrastructure and established the relationship $EDC = f(C)$, the present study extends these insights to system-level integration through five interacting subsystems: biomimetic intelligence, energy systems, community co-development, competence infrastructure, and resilience and feedback mechanisms.

The principal contribution lies in embedding competence infrastructure as an endogenous engineering subsystem while positioning communities as active contributors to system design, governance, and operation. Biomimetic principles further introduce adaptive capacity through mechanisms of redundancy, symbiosis, feedback, and distributed functionality.

By integrating previously fragmented technological, ecological, and human dimensions, the architecture provides a scalable foundation for resilient renewable energy deployment, particularly within Global South contexts characterized by infrastructural and institutional constraints.

Although developed as a systems engineering model, the framework establishes a basis for future empirical validation, quantitative modelling, and operational decision-support tools. More broadly, it contributes to the transition from static infrastructure models toward adaptive socio-technical energy systems capable of supporting long-term environmental sustainability and community-centred energy transitions.

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