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Beyond Agrivoltaics: A Governance-Embedded Socio-Technical Systems Architecture for Decentralized Agro-Industrial Ecosystems and Competence-Driven Rural Industrialization

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Abstract

Agrivoltaic systems have emerged as a promising strategy for addressing the water-energy-food nexus through the co-location of photovoltaic energy generation and agricultural production. However, existing agrivoltaic models are predominantly designed to optimize land-use efficiency, energy generation, and crop productivity, with limited attention to the institutional, technical, governance, and socio-economic conditions necessary for sustainable rural industrialization. This study proposes a governance-embedded socio-technical systems architecture that reconceptualizes agrivoltaics as the foundational energy infrastructure for decentralized agro-industrial ecosystems. Drawing upon systems engineering, biomimetic design principles, competence infrastructure, and community co-development, the study develops an integrated, layered framework that systematically links renewable energy generation, agricultural production, agro-processing, governance, engineering capability, institutional coordination, and adaptive resilience within a unified systems architecture. The methodology integrates conceptual synthesis, socio-technical systems architecture development, mathematical representation of subsystem interactions, and an illustrative pilot application based on a representative rural community in Nigeria. The proposed framework models the dynamic interactions among energy, material, information, governance, knowledge, and feedback flows to demonstrate how coordinated subsystem integration improves overall system performance, resilience, and sustainability. The illustrative application demonstrates the technical feasibility of a decentralized agrivoltaic energy node capable of supporting solar-powered irrigation, agro-processing, cold storage, and essential community services, while indicating significant potential to reduce post-harvest losses, increase local value addition, strengthen engineering competence, improve institutional capacity, and enhance community participation. By explicitly embedding governance, engineering competence, and community co-development as endogenous system variables, the proposed architecture advances agrivoltaics beyond conventional dual land-use optimization toward a scalable, adaptive, and competence-driven socio-technical framework for decentralized rural industrialization and sustainable development across the Global South.

Keywords
Agrivoltaics;
Socio-Technical Systems Engineering;
Engineering Competence Infrastructure;
Governance-Embedded Systems;
Agro-Industrial Development;
Rural Energy Systems; Nigeria

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1. Introduction

1.1 Industrialization, Rural Development and the Energy Transition

Industrialization has long been recognised as the principal mechanism through which economies achieve structural transformation, transitioning from predominantly agrarian production systems to diversified economies characterized by higher productivity, technological innovation, value addition, and sustained economic growth. Although industrialization pathways vary across countries, enduring economic transformation consistently depends on the effective integration of productive sectors through reliable infrastructure, technological capability, institutional effectiveness, and human capital development (UNIDO, 2022; Rodrik, 2021). Across Sub-Saharan Africa, however, industrial development remains spatially uneven. Rural communities, despite constituting the primary centres of agricultural production, continue to occupy peripheral positions within industrial value chains, functioning largely as suppliers of unprocessed agricultural commodities while opportunities for processing, manufacturing, and value addition remain concentrated in urban centres (World Bank, 2022; FAO, 2022).

Nigeria typifies this structural imbalance. Agriculture continues to underpin national employment, rural livelihoods, and food security, yet rural production systems are constrained by persistent deficits in electricity supply, transport infrastructure, storage facilities, agro-processing capacity, and institutional support. As a result, substantial volumes of agricultural produce leave farming communities in their primary form, while higher-value processing, industrial employment, and downstream economic benefits accrue elsewhere. This disconnect between agricultural production and industrial transformation contributes to post-harvest losses, low household incomes, youth unemployment, and sustained rural-urban migration. Recent studies further identify inadequate energy infrastructure, weak institutional coordination, governance deficiencies, and limited technological capability as persistent barriers to sustainable rural industrialization in Nigeria (Oyedepo, 2012; Onuh et al., 2024).

These structural constraints have stimulated renewed interest in alternative pathways for rural industrial development. Conventional industrialization strategies have historically depended on centralized electricity generation, large-scale industrial estates, and extensive transport infrastructure. While these approaches have contributed significantly to economic growth in many industrialized economies, they have demonstrated limited effectiveness within geographically dispersed rural settings characterised by inadequate infrastructure, constrained public investment, fragmented markets, and institutional variability (IEA, 2023). Consequently, increasing attention has shifted towards decentralized industrialization strategies in which energy generation is integrated directly with productive activities, particularly where the extension of centralized infrastructure remains economically or technically impracticable (IRENA, 2023; World Bank, 2022).

This evolving perspective has fundamentally repositioned energy from a social amenity to a productive asset that underpins agricultural mechanization, irrigation, cold-chain logistics, agro-processing, digital services, and rural manufacturing. Accordingly, contemporary rural development strategies increasingly emphasize productive energy systems capable of stimulating enterprise development, technological innovation, local value addition, and resilient community-based industrial growth rather than focusing exclusively on household electrification (IEA, 2023; FAO, 2022).

1.2 Agrivoltaics as an Enabling Platform for Decentralized Rural Industrialization

Among emerging renewable energy technologies, agrivoltaic systems have attracted considerable scholarly and policy attention because they simultaneously support food production, renewable electricity generation, climate resilience, and sustainable land management. By integrating photovoltaic electricity generation with agricultural production on the same parcel of land, agrivoltaics optimise land use while creating opportunities for multiple productive functions within a single spatial system. Since the pioneering work of Goetzberger and Zastrow (1982), extensive research has demonstrated that well-designed agrivoltaic systems can improve land equivalent ratios, moderate crop microclimates, conserve soil moisture, reduce heat stress, and enhance overall resource-use efficiency (Barron-Gafford et al., 2019; Weselek et al., 2019; Agostini et al., 2021). These advances have established agrivoltaics as an important component of the food-energy-water nexus and a promising technology for climate-smart agriculture.

Notwithstanding these advances, the dominant body of agrivoltaic research remains largely techno-centric. Existing studies have concentrated primarily on photovoltaic performance, system configuration, crop compatibility, irrigation management, environmental impacts, economic feasibility, and land-use optimisation. Comparatively limited attention has been directed towards examining how agrivoltaic infrastructure can function as an enabling platform for decentralized industrialization by supporting agro-processing, local enterprise development, productive energy utilisation, and rural manufacturing. This narrow analytical emphasis constrains the broader developmental potential of agrivoltaics, particularly in developing economies where engineering performance alone is insufficient to deliver sustained socio-economic transformation (Agostini et al., 2021; Weselek et al., 2019; Zahrawi & Aly, 2024).

Emerging evidence from Nigeria and other developing economies further suggests that the long-term performance of decentralized renewable energy systems depends not only on technological efficiency but also on the quality of governance, institutional coordination, stakeholder participation, and the availability of local engineering competence required for installation, operation, maintenance, and continuous system adaptation (Onuh et al., 2024; Oyedepo, 2012). These observations indicate that agrivoltaic systems should be understood not simply as dual land-use technologies but as productive energy infrastructure capable of underpinning decentralized agro-industrial ecosystems. Realising this broader potential, however, requires engineering architectures that integrate technological infrastructure with governance processes, competence infrastructure, and adaptive socio-technical system design rather than treating these dimensions as external implementation considerations.

1.3 Socio-Technical Systems, Governance and Competence Infrastructure

The transition towards decentralized rural industrialization extends beyond the deployment of renewable energy technologies to encompass the broader socio-technical systems within which such technologies are conceived, implemented, and sustained. Socio-technical systems theory provides an appropriate foundation for understanding these interactions by conceptualizing infrastructure as the outcome of continuous co-evolution among technological artefacts, institutions, governance arrangements, organizational structures, and human actors. From this perspective, engineering systems derive their long-term effectiveness not solely from technical performance but from the alignment of technological innovation with institutional capacity, adaptive governance, stakeholder participation, and organizational learning. Sustainable infrastructure therefore emerges as a property of the entire socio-technical system rather than of individual technological components.

Evidence from decentralized renewable energy systems increasingly supports this systems perspective. Studies consistently demonstrate that engineering reliability alone rarely guarantees sustained infrastructure performance, particularly within rural and resource-constrained environments. Rather, successful decentralized systems are characterised by governance arrangements that promote transparency, accountability, stakeholder participation, institutional legitimacy, and adaptive decision-making, alongside locally embedded maintenance structures capable of supporting continuous operation and technological adaptation. Community ownership models and participatory governance mechanisms have similarly been associated with improved infrastructure sustainability because they strengthen institutional trust, facilitate collective resource mobilization, reduce operational conflicts, and reinforce long-term system stewardship.

Complementing governance is the growing recognition that engineering competence constitutes a critical infrastructure in its own right. Beyond conventional notions of workforce training, competence infrastructure encompasses the institutional mechanisms through which technical knowledge is generated, transferred, retained, and continuously renewed across the engineering system. It incorporates technical education, vocational training, organizational learning, innovation networks, maintenance capability, entrepreneurial development, and institutional memory, collectively providing the adaptive capacity required for resilient infrastructure operation. Within decentralized production systems, where communities assume greater responsibility for system installation, operation, maintenance, and incremental innovation, competence infrastructure directly influences engineering reliability, operational efficiency, technological adaptation, and long-term sustainability.

Despite growing recognition of these interdependencies, governance and competence remain inadequately represented within mainstream engineering design methodologies. Existing infrastructure models typically regard governance structures, institutional arrangements, and technical capacity as external implementation conditions rather than endogenous components of system architecture. Consequently, many technically robust renewable energy projects experience declining functionality after deployment because governance processes, institutional ownership, maintenance capability, and local engineering competence receive considerably less design attention than hardware configuration or system efficiency. Such outcomes illustrate that infrastructure sustainability depends as much on institutional resilience and human capability as on technological performance.

Viewed collectively, contemporary scholarship reveals increasing convergence among research on rural industrialization, decentralized renewable energy, agrivoltaics, governance, and socio-technical systems. However, these domains continue to evolve largely in parallel rather than as components of an integrated engineering paradigm. Industrialization research seldom considers how decentralized renewable energy systems can be systematically embedded within localized production networks to catalyse endogenous industrial transformation (UNIDO, 2022; World Bank, 2022). Agrivoltaic research continues to prioritize technological optimisation while giving comparatively limited attention to governance processes, institutional capability, engineering competence, and locally retained value creation (Agostini et al., 2021; Weselek et al., 2019; Zahrawi & Aly, 2024). Likewise, socio-technical systems research has produced valuable conceptual insights but has only rarely translated these into operational engineering architectures that explicitly integrate governance, competence infrastructure, energy systems, agricultural production, and agro-industrial development within a unified framework suitable for rural African contexts.

1.4 Research Gap, Study Aim and Contributions

The Nigerian context underscores the urgency of addressing these interconnected challenges. Although national development policies increasingly advocate renewable energy deployment, agricultural modernization, local value addition, and rural industrialization, implementation continues to be constrained by fragmented institutional responsibilities, inconsistent governance arrangements, inadequate engineering capacity, and weak integration across the energy, agriculture, manufacturing, and community development sectors. These persistent structural constraints suggest that sustainable rural industrialization cannot be achieved through technological innovation alone but requires integrated engineering approaches capable of simultaneously addressing technological, institutional, organizational, and socio-economic dimensions of development.

Against this backdrop, four significant knowledge gaps become apparent. First, existing agrivoltaic research remains predominantly centred on dual land-use optimisation and renewable energy performance, with comparatively little attention devoted to its role as foundational infrastructure for decentralized industrialization and endogenous rural value creation. Second, governance mechanisms, despite their recognised importance for infrastructure sustainability and community ownership, remain largely absent from engineering system architectures and are seldom modelled as intrinsic design components. Third, engineering competence continues to be treated primarily as an implementation requirement rather than as an endogenous subsystem that shapes technological learning, adaptive maintenance, operational performance, innovation, and institutional resilience. Fourth, there is presently no integrated engineering framework that explicitly models the dynamic interactions among renewable energy generation, agricultural production, agro-processing, governance systems, competence infrastructure, community participation, and adaptive system feedback within a unified socio-technical architecture for decentralized rural industrialization.

This study addresses these gaps by developing a governance-embedded socio-technical systems architecture that reconceptualizes agrivoltaic infrastructure as the productive energy foundation of decentralized agro-industrial ecosystems. Rather than viewing agrivoltaics solely as a technology for improving land-use efficiency, the proposed framework positions it as the enabling infrastructure through which renewable energy generation, agricultural production, agro-processing, governance processes, competence infrastructure, and community co-development interact as mutually reinforcing engineering subsystems. Through this integration, the framework extends existing agrivoltaic research beyond technological optimisation towards an operational systems architecture for competence-driven rural industrial transformation. The framework is contextualized using Ovbieko, Nigeria, as a representative rural community whose developmental characteristics mirror many of the structural challenges confronting decentralized industrialization across Nigeria and Sub-Saharan Africa.

The study makes four principal contributions to knowledge. First, it advances agrivoltaic research beyond technical optimisation by establishing a systems engineering framework for decentralized rural industrialization. Second, it embeds governance and engineering competence infrastructure as endogenous architectural subsystems whose interactions directly influence overall system behaviour and long-term resilience. Third, it integrates energy, material, knowledge, governance, and value flows within a unified socio-technical architecture that captures the complex interdependencies underpinning sustainable rural transformation. Finally, it demonstrates how governance-informed systems engineering can be operationalized to support resilient, inclusive, and locally embedded agro-industrial ecosystems, thereby providing a practical pathway for decentralized industrial development in Nigeria and comparable developing economies.

To consolidate the preceding literature review and clarify the intellectual positioning of the present study, Table 1 synthesizes representative research across the principal domains informing this work. The comparison highlights the major contributions of existing scholarship, identifies persistent conceptual and architectural limitations, and demonstrates how the proposed governance-embedded socio-technical systems architecture addresses the resulting research gaps.

Table 1. Synthesis of representative literature, identified research gaps, and the contribution of the proposed governance-embedded socio-technical agrivoltaic systems architecture.

Research Theme	Representative Studies	Primary Contributions	Key Limitations	Research Gap	Contribution of This Study
Agrivoltaic Systems	Barron-Gafford et al. (2019); Weselek et al. (2019); Agostini et al. (2021); Zahrawi & Aly (2024)	Demonstrate co-location of photovoltaic systems with agriculture; improved land-use efficiency, crop productivity, and renewable energy generation.	Predominantly techno-economic and environmental; governance, institutional coordination, engineering competence, and community participation remain peripheral.	Lack of an integrated systems architecture linking agrivoltaics with governance and rural industrial development.	Develops a governance-embedded systems architecture integrating renewable energy, agriculture, engineering competence, community co-development, and institutional coordination.
Food–Energy–Water (FEW) Nexus	Hoff (2011); Albrecht et al. (2018); Purwanto et al. (2021)	Provides a holistic perspective on interactions among food, water, and energy resources for sustainable development.	Focuses on resource interdependencies rather than engineering implementation, governance architecture, or industrial transformation.	Limited operational guidance for decentralized agro-industrial systems.	Extends nexus thinking into an implementable socio-technical systems architecture with governance and industrialization pathways.
Decentralized Renewable Energy Systems	IRENA (2022); IEA (2023); World Bank (2022)	Demonstrate the role of distributed renewable energy in expanding rural electricity access and productive energy use.	Agriculture, governance, engineering competence, and value-chain integration are generally treated as contextual rather than architectural components.	Absence of integrated frameworks linking productive energy use with decentralized rural industrialization.	Positions renewable energy as the enabling layer within a broader governance-embedded agro-industrial ecosystem.
Socio-Technical	Geels (2002); Markard et al.	Explain how technological	Conceptual transition	Need for engineering-	Integrates socio-technical transition

Research Theme	**Representative Studies**	**Primary Contributions**	**Key Limitations**	**Research Gap**	**Contribution of This Study**
Systems and Sustainability Transitions	(2012); Bridge et al. (2013)	change is influenced by institutions, policy, stakeholders, and multi-level transitions.	frameworks seldom provide engineering architectures suitable for implementation or system design.	oriented socio-technical architectures supporting decentralized infrastructure systems.	principles within a layered systems engineering architecture for agrivoltaic development.
Community Energy and Rural Development	Walker & Devine-Wright (2008); Hicks & Ison (2018); IRENA (2022)	Highlight community ownership, stakeholder participation, social acceptance, and local empowerment.	Limited treatment of engineering competence, agro-processing, governance integration, and adaptive system evolution.	Need for a unified framework connecting community participation with productive infrastructure and industrial value creation.	Embeds community co-development within governance, engineering competence, adaptive resilience, and agro-industrial value chains.
Systems Engineering and Architecture	Hevner et al. (2004); Peffers et al. (2007); INCOSE (2023); ISO/IEC/IEEE 42010:2022	Provide methodologies for conceptual architecture development, systems integration, and design science research.	Rarely applied to governance-embedded agrivoltaic systems or decentralized rural industrial ecosystems.	Lack of reference architectures for integrated agrivoltaic socio-technical systems.	Proposes a reference systems architecture that synthesizes systems engineering, governance, renewable energy, agriculture, and adaptive resilience into a unified conceptual framework.

The synthesis demonstrates that although existing studies have substantially advanced agrivoltaic engineering, decentralized renewable energy, socio-technical transitions, and systems engineering, these domains continue to evolve largely in isolation. None provides an integrated engineering architecture that simultaneously embeds governance, engineering competence, community co-development, adaptive resilience, and agro-industrial value creation within a unified socio-technical framework. This synthesis therefore establishes the methodological justification for developing the architecture presented in the following section.

2. Methodology

2.1 Research Design and Systems Engineering Approach

This study adopted a qualitative systems engineering research design to develop a governance-embedded socio-technical architecture for decentralized rural industrialization through agrivoltaic-enabled production systems. The choice of a systems engineering approach reflects the inherently complex nature of rural industrial transformation, which emerges from dynamic interactions among technological infrastructure, governance arrangements, engineering competence, agricultural production, community participation, institutional processes, and environmental conditions. Unlike reductionist engineering approaches that optimize isolated technical components, systems engineering conceptualizes infrastructure as an integrated socio-technical system whose overall behaviour arises from the interaction of multiple interdependent subsystems operating across different organizational and functional scales (INCOSE, 2023; ISO/IEC/IEEE 15288:2023).

The study is conceptual, architecture-driven, and design-oriented. Rather than evaluating the operational performance of an existing agrivoltaic installation, it develops a generalized engineering architecture capable of supporting decentralized agro-industrial development in rural communities. The methodology therefore emphasizes system definition, architectural synthesis, interaction modelling, and contextual application instead of experimental testing or statistical hypothesis evaluation. This approach is consistent with contemporary systems engineering practice, where conceptual architectures provide the analytical foundation for subsequent simulation, optimization, implementation, and empirical validation.

2.1.1 Methodological Foundation for Conceptual Systems Architecture

This study is grounded in systems engineering and Design Science Research (DSR), which recognize conceptual architectures and frameworks as valid research outputs for addressing complex socio-technical problems (Hevner et al., 2004; Peffers et al., 2007). The study therefore develops a governance-embedded socio-technical architecture for decentralized agro-industrial development rather than evaluating an existing installation.

This methodological position is supported by INCOSE (2023) and ISO/IEC/IEEE 15288:2023, which identify architecture definition as a core systems engineering activity that integrates stakeholder needs, system functions, component interactions, and lifecycle considerations prior to detailed design and implementation.

A conceptual architecture is particularly appropriate for decentralized agro-industrial ecosystems, where governance, institutional coordination, engineering competence, community participation, environmental interaction, and resilience interact with technological systems. Because these dimensions form a complex adaptive socio-technical system, architecture-driven conceptualization provides a rigorous basis for integrating heterogeneous subsystems before detailed modelling or field deployment.

The proposed framework is therefore presented as a systems engineering reference architecture that establishes conceptual relationships among energy infrastructure, agricultural production, governance, competence development, community co-development, and adaptive resilience, and is intended to guide future simulation, implementation, policy development, and empirical validation.

2.2 Formal System Representation

The proposed framework is conceptualized as a coupled socio-technical system comprising interacting engineering, institutional, environmental, and community subsystems operating within a shared rural production environment. Formally, the system is represented as

$$S = (L, A, E, C, G, X) \quad (1)$$

where S denotes the overall system state comprising energy availability, agricultural productivity, agro-industrial capacity, governance effectiveness, engineering competence, community capability, and ecosystem resilience; L denotes the set of system layers; A represents agents including community members, engineers, and institutions; E denotes environmental conditions including policy and climate; C represents competence infrastructure; G denotes governance structures; and X represents cross-layer interactions.

The layered architecture is defined as:

$$L = (L_B, L_E, L_A, L_K, L_G, L_C, L_R) \quad (2)$$

where L_B represents *the biomimetic intelligence layer*, providing adaptive design principles inspired by resilience, redundancy, distributed functionality, and symbiotic resource utilization; L_E represents the decentralized energy subsystem centered on agrivoltaic electricity generation and energy management; L_A denotes agricultural production and resource management; L_K represents community co-development, responsible for fostering community capability, social organization, participatory decision-making, local enterprise development, value-chain integration, human capital formation, financial inclusion, social innovation, collective ownership, and the co-creation of socio-economic value necessary for sustainable decentralized agro-industrial development; L_G denotes governance infrastructure responsible for institutional coordination, accountability, planning, and resource allocation; L_C represents engineering competence infrastructure comprising technical education, knowledge transfer, innovation, maintenance capability, and organizational learning; and L_R represents adaptive resilience and feedback mechanisms that enable continuous system learning and long-term sustainability/

This layered representation recognizes decentralized industrialization as an emergent property of coordinated interactions among technological, institutional, organizational, and human subsystems rather than the outcome of technological deployment alone.

2.3 Architecture Development Procedure

The architecture was developed through three sequential and iterative stages.

The first stage involved conceptual synthesis, drawing upon literature on rural industrialization, agrivoltaics, decentralized renewable energy systems, socio-technical systems engineering, governance, and engineering competence infrastructure. Rather than reviewing these domains independently, common functional principles and recurring system variables were identified and synthesized into a unified conceptual model.

The second stage involved systems decomposition and architectural integration. Functional analysis was used to identify the principal engineering subsystems required for decentralized rural industrialization, while interaction modelling established the relationships among energy generation, agricultural production, agro-processing, governance processes, competence development, and community participation. The resulting architecture was subsequently organized into interacting system layers governed by adaptive feedback mechanisms.

The third stage involved contextual application using Ovbieko, Nigeria, as a representative rural community. The case was employed to demonstrate the operational applicability of the proposed architecture within a realistic socio-economic environment characterized by agricultural dependence, unreliable electricity supply, limited agro-processing capacity, institutional fragmentation, and constrained technical capability. The objective was not statistical generalization but engineering contextualization, illustrating how the proposed architecture may be operationalized within comparable rural communities.

2.4 Dynamic Interaction Modelling

The proposed socio-technical architecture is characterized by continuous interactions among energy, material, knowledge, governance, and adaptive feedback processes. These interactions are collectively represented by the system flow vector

$$F = (F_e, F_m, F_k, F_g, F_r \qquad (3)$$

where F_e denotes energy flows generated and distributed through the agrivoltaic infrastructure; F_m represents material flows associated with agricultural production, storage, processing, and value addition; F_k denotes knowledge and competence flows arising from education, technical training, innovation, and organizational learning; F_g represents governance flows encompassing institutional coordination, stakeholder participation, policy implementation, accountability, and resource allocation; while F_r denotes adaptive feedback flows through which system performance continuously informs operational adjustment, governance decisions, learning, and long-term system adaptation.

Overall system performance is assumed to emerge from the interaction of these functional flows with the layered architecture, participating agents, and external environmental conditions, and is expressed as

$$P = f(F, L, A, E) \qquad (4)$$

where P denotes overall system performance, F is the vector of functional flows defined in Equation (3), L represents the layered socio-technical architecture, A denotes the set of interacting system agents (including communities, institutions, enterprises, and technical actors), and E represents external environmental conditions such as climate, market dynamics, regulatory policies, and socio-economic factors.

To describe the temporal evolution of the integrated system, the framework adopts a nonlinear state-space representation

$$\frac{dS}{dt} = \Phi(S, F, E) \qquad (5)$$

where S denotes the overall system state defined in Equation (1), while Φ (Phi) represents the nonlinear transformation operator governing state transitions arising from interactions among internal system components and external environmental influences.

Although the present study does not undertake numerical simulation, Equations (3) - (4) provide a formal systems-engineering foundation for future implementation using system dynamics, agent-based modelling, digital twins, or other computational simulation approaches capable of evaluating system behaviour under alternative governance, technological, and environmental scenarios.

From a systems engineering perspective, these mathematical representations establish the formal behavioural specification of the proposed architecture rather than a fully parameterized simulation model. Their principal function is to define subsystem interactions, information flows, and governing relationships that can subsequently be instantiated within computational environments such as System Dynamics, Agent-Based Modelling, Model-Based Systems Engineering (MBSE), or Digital Twin platforms.

2.5 Scope and Contextual Boundaries

The proposed framework is limited to conceptual systems design and engineering architecture development. It does not undertake electrical performance simulation, economic optimization, life-cycle assessment, crop-specific agronomic modelling, or financial feasibility analysis. Instead, the study establishes an integrated engineering framework within which these analyses may subsequently be incorporated.

Although illustrated using Ovbieko as a representative rural community, the framework is intended to function as a transferable reference architecture whose engineering principles may be adapted to comparable decentralized agro-industrial contexts following appropriate socio-economic, environmental, governance, and technical calibration. Consistent with systems engineering practice, the architecture provides a conceptual baseline upon which future simulation, digital twin development, techno-economic assessment, lifecycle analysis, and empirical implementation studies may be progressively constructed.

3. Proposed Layered Socio-Technical Systems Architecture

3.1 Overall System Architecture

The proposed framework conceptualizes agrivoltaic development as an integrated socio-technical ecosystem rather than a stand-alone renewable energy technology. The proposed architecture embeds governance, engineering competence development, community co-development, agro-industrial value addition, and adaptive resilience within a unified systems engineering framework, contrary to conventional agrivoltaic systems, which primarily combine photovoltaic electricity generation with agricultural production.

The architecture is founded on systems thinking, whereby sustainable rural industrialization emerges from coordinated interactions among technological, institutional, environmental, economic, and social subsystems. Rather than optimizing isolated components, the framework emphasizes system-wide integration, feedback, and adaptive learning to achieve long-term resilience. Accordingly, the overall architecture is represented as defined in equation (2)

Collectively, these layers define the functional architecture through which energy generation, agricultural production, industrial value addition, institutional coordination, competence development, and community participation interact as an integrated rural development ecosystem.

To provide a holistic overview of the proposed framework, Figure 1 presents the governance-embedded multi-layered socio-technical systems architecture, illustrating the principal architectural layers, their functional relationships, and the integration of technological, institutional, economic, and community subsystems within a unified decentralised agro-industrial ecosystem.

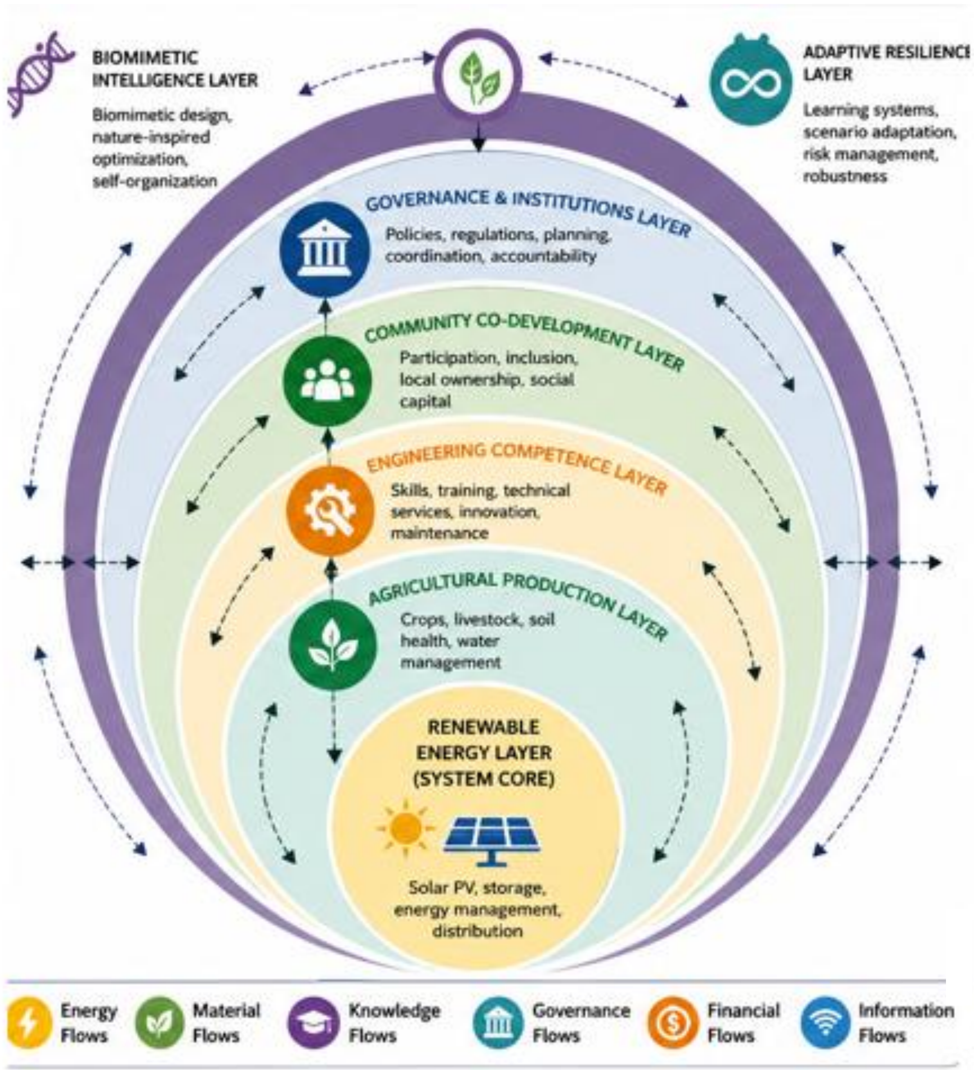

Figure 1: Governance-Embedded Multi-Layered Socio-Technical Systems Architecture for Decentralized Agro-Industrial Agrivoltaic Ecosystems

Figure 1 presents the proposed governance-embedded multi-layered socio-technical systems architecture, illustrating a seven-layer ecosystem in which the renewable energy core enables agricultural production and agricultural value addition, supported by engineering competence development, community participation, and strong governance, while adaptive resilience and biomimetic intelligence drive continuous learning and system evolution. Collectively, these interconnected layers demonstrate that sustainable agro-industrial transformation depends on the coordinated interaction of technological, institutional, economic, and social subsystems rather than on isolated engineering interventions. The proposed architecture therefore provides an integrated framework capable of simultaneously supporting renewable energy generation, agricultural productivity, local value addition, and long-term rural industrial development. The following subsections examine the functional roles and interactions of these architectural layers in greater detail.

3.2 Functional Relationships among Layers

The layered architecture is designed to capture both vertical and horizontal interactions among system components. Vertically, energy generated within the agrivoltaic subsystem provides the operational backbone supporting irrigation, agro-processing, storage, education, and community services. Horizontally, governance coordinates resource allocation, engineering competence sustains technical operation and innovation, community co-development facilitates stakeholder participation and ownership, while adaptive resilience continuously monitors overall system performance and facilitates learning.

These interactions establish mutually reinforcing feedback loops that improve operational efficiency, strengthen institutional capacity, and enhance long-term sustainability. Dissimilar to conventional engineering systems that emphasize linear input-output relationships, the proposed architecture behaves as a dynamic adaptive socio-technical ecosystem in which each subsystem simultaneously functions as both a service provider and service recipient within the broader network.

3.3 Information, Energy and Resource Integration

The proposed architecture integrates five principal categories of system flows:

i. electrical energy flows,
ii. agricultural material flows,
iii. knowledge and competence flows,
iv. governance and institutional flows,
v. adaptive feedback flows.

These interacting flows create continuous exchanges among the seven architectural layers, ensuring that system behaviour emerges from coordinated interactions rather than isolated subsystem performance. The multidirectional interactive relationships function as the enabling backbone while governance, competence development, and community co-development regulate adaptive operation across the entire agro-industrial ecosystem.

3.4 Architectural Novelty

The principal contribution of the proposed architecture lies in extending agrivoltaic systems beyond electricity generation and agricultural production to encompass the broader institutional and socio-economic mechanisms required for sustainable rural industrialization.

Three key innovations distinguish the framework from existing agrivoltaic models.

First, governance infrastructure is explicitly incorporated as an engineering subsystem responsible for institutional coordination, accountability, policy implementation, and resource allocation.

Second, engineering competence infrastructure is integrated as a formal system component responsible for workforce development, technical education, innovation, organizational learning, and long-term operational capability.

Third, community co-development is elevated from a stakeholder engagement activity to a dynamic subsystem that actively shapes planning, implementation, resource mobilization, entrepreneurship, value-chain development, and local ownership through continuous collaboration among communities, government agencies, educational institutions, private-sector organizations, financial institutions, and development partners.

Consequently, the framework transforms agrivoltaics from a renewable energy technology into a governance-embedded, competence-driven, and community-centred socio-technical architecture capable of supporting decentralized agro-industrial ecosystems across the Global South.

Having established the conceptual foundations of the proposed architecture, it is useful to summarize the principal innovations that distinguish the framework from conventional agrivoltaic systems. Table 2 presents a concise comparison of the major architectural characteristics, highlighting the broader systems engineering perspective adopted in this study.

Table 2: System Innovation Compared with Conventional Agrivoltaic Frameworks

Conventional Agrivoltaics	Proposed System Innovation Framework
Energy + crops	Energy + crops + agro-processing
Farm-scale optimization	Regional socio-technical ecosystem
Land-use efficiency	Rural industrialization
Technical performance	Technical + governance performance
No competence model	Competence infrastructure embedded
Static configuration	Adaptive multi-layer architecture
Limited stakeholder integration	Community co-development and governance
Limited economic integration	Complete agro-industrial value chain

As summarized in Table 2, the proposed framework extends agrivoltaics beyond dual land-use optimization by embedding governance, engineering competence, adaptive resilience, community co-development, and complete agro-industrial value-chain integration within a unified systems architecture. These innovations collectively reposition agrivoltaic infrastructure as the enabling foundation for decentralized rural industrialization rather than merely a renewable energy technology.

To further clarify the operational organization of the proposed architecture, Table 3 summarizes the functional responsibilities of each architectural layer together with the principal actors responsible for implementation and the expected system outputs. This overview illustrates how individual layers contribute collectively to the operation of the integrated socio-technical ecosystem.

Table 3: Functional Roles of Each Architectural Layer

Architectural Layer	Primary Function	Main Actors	Expected Outputs
Renewable Energy	Electricity generation and management	Utilities, operators	Reliable productive energy
Agricultural Production	Crop and livestock production	Farmers, cooperatives	Increased productivity
Engineering Competence	Technical training, maintenance, innovation	Universities, TVETs, engineers	Skilled workforce
Community Co-development	Participation, inclusion, ownership	Communities, NGOs	Social capital
Governance & Institutions	Policy, regulation, coordination	Government, regulators	Institutional resilience
Adaptive Resilience	Monitoring, learning, adaptation	All stakeholders	Long-term sustainability
Biomimetic Intelligence	Nature-inspired optimization	Researchers, designers	System innovation

Collectively, the functional roles summarized in Table 3 demonstrate that sustainable system performance emerges through coordinated interactions among technological, institutional, organizational, and community subsystems rather than through isolated engineering components. This functional decomposition provides the conceptual basis for the mathematical interaction models developed in Section 4.

3.5 Transition to Dynamic System Modelling

Having established the structural organization of the proposed layered architecture, the subsequent section formalizes the interactions among these subsystems through mathematical representations of energy flows, material transformations, governance processes, competence development, community participation, and adaptive feedback. These formulations provide a systems engineering foundation for analysing dynamic behaviour, evaluating performance, and supporting future simulation, optimization, and digital twin implementation.

4. Functional Modelling of the Integrated Socio-Technical Agro-Industrial Agrivoltaic System

Having established the layered architecture in Section 3, this section formalizes the functional behaviour of the proposed system through subsystem-level mathematical representations. The objective is not to develop a numerical simulation model but to establish a systems engineering formulation that describes how energy generation, agricultural production, governance, engineering competence, community co-development, and adaptive resilience interact to produce sustainable rural industrialization.

4.1 Agrivoltaic Energy Infrastructure Subsystem

The agrivoltaic energy subsystem *(L_E)* constitutes the primary enabling infrastructure of the proposed architecture. It converts incident solar radiation into electrical energy for agricultural production, agro-processing, community services, and institutional operations. Unlike conventional electrification systems, the generated energy supports both productive and social functions within the rural ecosystem.

The agrivoltaic energy subsystem converts incident solar radiation into electrical energy according to established photovoltaic conversion principles, which form the primary energy source for the integrated agro-industrial system. Equation (3) establishes the primary energy input that drives all downstream socio-technical processes.

4.2 Agro-Industrial Production Subsystem

The agricultural subsystem (L_A) extends beyond crop cultivation by integrating processing and value addition within the same system boundary. Agricultural products therefore become inputs into decentralized agro-industrial production rather than terminal outputs.

4.3 Community Co-Development Subsystem

Community co-development (L_K) functions as a collaborative subsystem through which local stakeholders actively participate in planning, implementation, governance, entrepreneurship, capacity development, resource mobilization, and long-term ownership of the agro-industrial ecosystem. Rather than serving merely as beneficiaries, community actors become co-designers and co-managers of system evolution. Higher levels of participation, trust, and local investment strengthen system sustainability and adaptive capacity.

4.4 Governance and Institutional Coordination

The governance subsystem (L_G) provides institutional coordination, transparency, accountability, strategic planning, and resource allocation. Drawing upon lessons from the Ovbieko rural governance model, governance is treated as an engineering subsystem that stabilizes interactions among technological, social, and economic components.

4.5 Engineering Competence Infrastructure

The competence infrastructure subsystem (L_C) supplies the technical capabilities required for installation, operation, maintenance, innovation, and continuous improvement of the agro-industrial ecosystem. Competence is treated as a dynamic system variable rather than a static workforce characteristic.

Competence evolution is represented as

$$\frac{dC}{dt} = y1T_r + y2S_m + y3D_f \qquad (6)$$

Where C denotes engineering competence, T_r is the training rate, S_m represents simulation-based learning, D_f denotes diagnostic feedback, γ_i are competence growth coefficients.

This formulation reflects continuous workforce development through learning and operational feedback.

4.6 Biomimetic Intelligence and Adaptive Resilience

The biomimetic layer (L_B) governs adaptive system behaviour by emulating principles observed in resilient natural ecosystems, including redundancy, modularity, distributed control, and symbiotic resource utilization. These principles regulate energy allocation, agricultural production, and institutional adaptation under changing environmental conditions.

The resilience subsystem (L_R) integrates system-wide monitoring and adaptive feedback, enabling continuous performance evaluation and iterative improvement. Rather than functioning as an independent component, resilience emerges from coordinated interactions among all architectural layers.

Together, these subsystems establish the functional relationships that underpin the integrated socio-technical agro-industrial architecture.

5. Illustrative Application: Governance-Embedded Rural Agro-Industrial Agrivoltaic Cluster

Rather than presenting the proposed framewor solely as a theoretical systems architecture, this section demonstrates its operational applicability through an illustrative rural agro-industrial cluster representing conditions commonly encountered across southern Nigeria. The illustrative application is not intended as an empirical case study or statistical validation; rather, it functions as an engineering demonstration that translates the proposed socio-technical architecture into a realistic implementation scenario. By contextualizing the framework within a representative rural environment, the study illustrates how coordinated interactions among renewable energy infrastructure, agricultural production, governance, engineering competence, and community participation can facilitate decentralized industrial transformation.

5.1 System Context and Baseline Conditions

The illustrative application is based on a representative rural community modelled after the socio-economic characteristics of Ovbieko in Edo State, Nigeria. The community typifies many agricultural settlements across Sub-Saharan Africa where farming constitutes the dominant livelihood, electricity supply remains unreliable, agro-processing capacity is limited, and significant post-harvest losses constrain household incomes and rural economic development.

Agriculture is predominantly rain-fed, processing activities depend heavily on diesel-powered equipment, and market participation is restricted by inadequate storage facilities, poor transport logistics, and limited institutional coordination among producers, cooperatives, financial institutions, extension services, and local government agencies.

Within this baseline scenario, renewable energy deployment alone would be insufficient to stimulate sustainable industrialization. Instead, the proposed architecture assumes that productive transformation emerges through the coordinated integration of technological infrastructure with governance systems, competence development, institutional collaboration, and adaptive community participation. Consequently, agrivoltaic infrastructure is conceptualized not as an isolated electricity-generation asset but as the foundational energy platform around which decentralized agro-industrial ecosystems evolve.

5.2 Phased Engineering Implementation Pathway

Implementation is conceptualized as a progressive systems engineering process comprising eight mutually reinforcing phases. The successful implementation of the proposed architecture requires a structured sequence of engineering, institutional, and community development activities. Figure 2 outlines the recommended implementation pathway, demonstrating the progression from foundational system preparation to long-term agro-industrial transformation.

Figure 2: Phased Implementation Pathway for Governance-Embedded Agro-Industrial Development

Figure 2 highlights that effective deployment is inherently progressive, with each implementation phase establishing the technical, organizational, and governance capacities required for subsequent stages. The phased activities associated with this pathway are described in the following subsections.

Phase 1: Agrivoltaic Infrastructure Deployment - Photovoltaic arrays are integrated with agricultural production to establish the primary energy platform supporting productive and community activities.

Phase 2: Productive Energy Integration - Generated electricity is allocated to solar-powered irrigation, borehole pumping, lighting, telecommunications, educational facilities, and primary healthcare infrastructure.

Phase 3: Agro-Industrial Value Addition - Renewable electricity supports decentralized processing facilities for cassava, maize, vegetables, and other agricultural products, enabling local transformation, packaging, storage, and quality assurance.

Phase 4: Cold-Chain Development - Solar-powered refrigeration and cold storage facilities reduce post-harvest losses while extending product shelf life and improving market competitiveness.

Phase 5: Engineering Competence Development - Continuous technical training programmes strengthen local capability in photovoltaic installation, preventive maintenance, equipment diagnostics, agro-processing technologies, digital monitoring, and systems management.

Phase 6: Digital Market Integration - Digital platforms facilitate market information, logistics coordination, cooperative management, financial inclusion, and electronic commerce, thereby strengthening rural participation in regional agricultural value chains.

Phase 7: Governance Consolidation - Community cooperatives, local government, private investors, educational institutions, financial organizations, and development partners collaborate through transparent governance structures responsible for planning, resource allocation, performance monitoring, and conflict resolution.

Phase 8: Adaptive Learning and System Expansion - Performance monitoring continuously informs system refinement, infrastructure expansion, policy adjustment, competence upgrading, and investment prioritization, thereby strengthening long-term system resilience.

5.3 Integrated Resource and Value Flows

Within the proposed architecture, electrical energy functions as the enabling resource from which multiple productive flows emerge. Renewable electricity simultaneously supports irrigation, agricultural production, agro-processing, cold-chain infrastructure, educational institutions, healthcare services, digital communication networks, and community enterprises. Agricultural outputs subsequently become inputs for decentralized processing facilities, while processed products enter regional markets through cooperative distribution systems.

The resulting financial returns are partially reinvested into infrastructure maintenance, engineering education, equipment replacement, community services, and enterprise development. Consequently, energy, materials, financial resources, institutional knowledge, and governance information circulate continuously throughout the architecture, creating reinforcing feedback loops that improve long-term sustainability.

Knowledge represents an equally critical system resource. Universities, vocational institutions, extension agencies, engineering practitioners, and local enterprises collectively generate technical competence that supports installation, preventive maintenance, innovation, organizational learning, and continuous technological adaptation. Rather than functioning independently, physical infrastructure and human capability evolve together as complementary drivers of decentralized industrialization. To illustrate how the proposed architecture functions after deployment, Figure 3 presents the operational progression through which coordinated resource flows, governance processes, productive activities, and continuous learning collectively drive sustainable rural industrialisation.

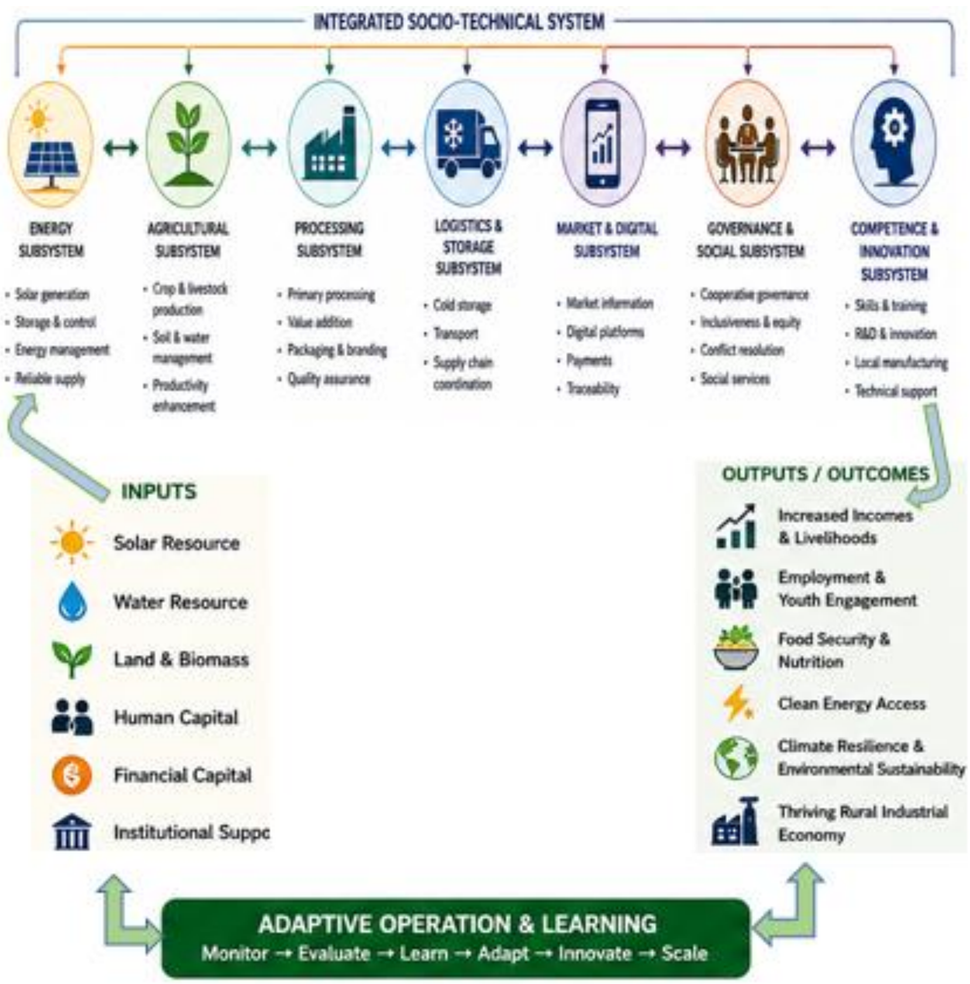

Figure 3: Integrated Operational Model for Governance-Embedded Agro-Industrial Agrivoltaic Systems

Figure 3 demonstrates that the proposed architecture operates as an adaptive socio-technical system in which engineering processes, governance mechanisms, resource utilisation, and stakeholder interactions reinforce one another through continuous feedback and improvement. These integrated operational processes ultimately underpin the sustainable development outcomes discussed in the subsequent section.

5.4 Expected System Outcomes

Although the illustrative application is conceptual, the proposed architecture enables identification of measurable performance indicators suitable for future empirical evaluation. Engineering performance may be assessed through annual electricity generation, photovoltaic system availability, equipment reliability, irrigation coverage, agro-processing capacity, cold-storage utilization, and renewable energy penetration. Agricultural performance may be evaluated using crop productivity, reductions in post-harvest losses, processing efficiency, and value-added agricultural output.

Socio-economic performance indicators include employment generation, household income growth, enterprise formation, local investment, cooperative participation, and market integration. Governance performance may be assessed using institutional transparency, stakeholder participation, maintenance responsiveness, accountability mechanisms, and collaborative decision-making. Engineering competence may be evaluated through technician certification, maintenance capability, workforce retention, innovation activities, and knowledge-transfer effectiveness.

Collectively, these multidimensional indicators provide an integrated evaluation framework through which future implementation projects may assess both engineering performance and broader socio-economic transformation.

5.5 Illustrative Socio-Technical Transformation

Assuming a representative rural community of approximately 5,000 residents, supported by a 1 MW agrivoltaic installation operating under an average annual solar resource of approximately 5.5 kWh m^{-2} day^{-1} and photovoltaic conversion efficiency of 18%, the integrated system is capable of generating approximately 1.8 GWh of renewable electricity annually. This energy simultaneously supports agricultural production, decentralized agro-processing, cold-chain logistics, educational facilities, healthcare infrastructure, community enterprises, and essential public services.

Unlike conventional rural electrification projects, the proposed architecture treats electricity as productive infrastructure embedded within governance systems, engineering competence networks, agro-industrial value chains, and community institutions. Renewable energy therefore becomes the catalyst for coordinated socio-economic transformation rather than an isolated technological intervention. Increased processing capacity reduces post-harvest losses, strengthens local value addition, creates skilled employment opportunities, stimulates entrepreneurship, improves institutional collaboration, and reinforces long-term community resilience.

The illustrative application therefore demonstrates how decentralized agrivoltaic infrastructure can evolve beyond renewable electricity generation into an integrated governance-embedded socio-technical ecosystem capable of supporting sustainable rural industrialization. Although conceptual, the application provides a practical systems engineering blueprint upon which future digital twin development, system simulation, techno-economic optimization, lifecycle assessment, and empirical implementation studies may be undertaken.

5.6 Comparative Validation of the Proposed Systems Architecture

As a conceptual systems engineering study, the present research does not seek to validate the proposed architecture through field experimentation or numerical simulation. Rather, consistent with Design Science Research and systems architecture evaluation practices, validation is undertaken by comparing the proposed framework against representative conceptual approaches currently employed within agrivoltaic systems, decentralized renewable energy systems, and socio-technical infrastructure studies. The objective is to determine whether the proposed architecture provides broader functional coverage and greater systems integration than existing frameworks while addressing the research gaps identified in Section 1.

Before undertaking a detailed comparative evaluation, it is useful to visualize the relative systems engineering scope of the proposed framework against representative conceptual approaches identified in the literature. Figure 4 provides this high-level comparison across the principal functional dimensions considered in the present study

Figure 4: Comparative Systems Engineering Coverage of Representative Conceptual Frameworks

Figure 4 compares the systems engineering coverage of representative conceptual frameworks against the proposed architecture across the principal functional dimensions considered in this study, illustrating the extent to which each framework incorporates governance, engineering competence, community participation, adaptive resilience, agro-industrial value-chain integration, and future digital capabilities. The comparison demonstrates that the proposed framework achieves substantially broader functional integration than existing approaches by embedding these complementary dimensions within a single governance-oriented socio-technical architecture. This high-level visual comparison establishes the context for the detailed comparative evaluation presented in Table 4 and reinforces the principal conceptual contribution of the present study.

Existing agrivoltaic frameworks have predominantly emphasized photovoltaic performance, crop compatibility, land-use efficiency, and techno-economic optimization. Although these studies have significantly advanced agrivoltaic engineering, governance arrangements, engineering competence, institutional coordination, community co-development, and adaptive organizational learning generally remain external implementation considerations rather than explicit architectural components. Similarly, broader socio-technical systems research recognizes the importance of institutional and stakeholder interactions but seldom translates these concepts into operational engineering architectures capable of guiding decentralized agro-industrial development.

To assess the relative contribution of the proposed framework, six representative conceptual perspectives were selected for comparison: (i) conventional agrivoltaic systems, (ii) Food–Energy–Water (FEW) nexus frameworks, (iii) decentralized renewable energy systems, (iv) socio-technical transition frameworks, (v) community energy system models, and (vi) the governance-embedded socio-technical architecture proposed in this study. The comparison evaluates each framework across ten systems engineering criteria representing the principal dimensions required for decentralized rural industrialization.

The comparison demonstrates that conventional agrivoltaic frameworks perform strongly with respect to renewable energy generation, agricultural productivity, and land-use optimization but provide comparatively limited treatment of governance, institutional coordination, engineering competence, adaptive learning, and industrial value creation. Food–Energy–Water nexus models effectively represent resource interdependencies but generally stop short of modelling engineering implementation, governance mechanisms, or industrial development pathways. Decentralized renewable energy frameworks provide important insights into distributed electricity systems yet frequently treat agriculture, governance, and competence development as contextual rather than architectural variables. Likewise, socio-technical transition and community energy frameworks emphasize stakeholder participation, institutional change, and policy evolution but rarely integrate these elements into a unified engineering systems architecture capable of supporting agro-industrial production.

By contrast, the proposed governance-embedded socio-technical architecture simultaneously integrates renewable energy infrastructure, agricultural production, agro-processing, governance systems, engineering competence, community co-development, biomimetic resilience, adaptive learning, and industrial value creation within a single layered engineering framework. This broader integration enables coordinated management of technological, institutional, organizational, and human subsystems while preserving the engineering relationships necessary for future simulation, digital twin implementation, optimization, and empirical evaluation.

The comparative assessment therefore supports the principal contribution of this research: rather than replacing existing agrivoltaic models, the proposed architecture extends them into a comprehensive systems engineering framework suitable for competence-driven decentralized rural industrialization. The framework should consequently be interpreted as a reference architecture capable of integrating existing agrivoltaic technologies with governance structures, institutional processes, engineering capability, and community participation to achieve more resilient and inclusive rural development.

To complement the preceding qualitative assessment, Table 4 summarizes the comparative evaluation of the proposed architecture against representative conceptual frameworks using ten systems engineering criteria relevant to decentralized rural industrialization. The comparison provides a structured basis for assessing the breadth of functional integration achieved by the proposed framework.

Table 4. Comparative Evaluation of Representative Frameworks

Systems Engineering Criterion	Conventional Agrivoltaics	FEW Nexus	Decentralized Renewable Energy	Socio-Technical Systems	Community Energy	Proposed Framework
Renewable energy integration	✓	✓	✓	△	✓	✓
Agricultural production	✓	✓	△	△	△	✓
Agro-processing integration	✗	△	△	✗	△	✓
Governance architecture	✗	✗	△	✓	✓	✓
Engineering competence	✗	✗	✗	△	△	✓
Community co-development	△	△	△	✓	✓	✓
Adaptive resilience	△	△	△	✓	△	✓
Industrial value-chain integration	✗	✗	△	✗	✗	✓
Digital systems readiness	✗	✗	△	△	△	✓

Systems Engineering Criterion	Conventional Agrivoltaics	FEW Nexus	Decentralized Renewable Energy	Socio-Technical Systems	Community Energy	Proposed Framework
Future digital twin suitability	△	✗	△	△	✗	✓

Legend: ✓ = Explicitly incorporated; △ = Partially addressed; ✗ = Not explicitly addressed.

The comparative evaluation confirms that the proposed architecture is the only framework that explicitly integrates renewable energy, agricultural production, agro-processing, governance, engineering competence, community co-development, adaptive resilience, industrial value-chain development, and future digital twin readiness within a single layered systems engineering architecture. These findings support the principal contribution of the study and provide a natural foundation for the broader implications discussed in the following section.

6. Discussion

The proposed framework advances agrivoltaic systems beyond conventional dual land-use configurations by embedding agro-industrial value chains, governance infrastructure, engineering competence, and community co-development within a unified socio-technical architecture. Unlike existing models that primarily optimize energy generation and agricultural productivity, the proposed architecture recognizes that long-term system performance depends equally on institutional effectiveness, technical capability, stakeholder participation, and adaptive learning.

From a systems engineering perspective, the framework contributes a layered architectural model in which technological and social subsystems interact through continuous feedback mechanisms. The integration of biomimetic principles further strengthens resilience by enabling adaptive responses to environmental variability, infrastructure disruptions, and evolving community needs.

By explicitly modelling governance, competence, and community co-development as engineering subsystems rather than external contextual factors, the framework addresses critical barriers that frequently constrain renewable energy projects in developing economies. Consequently, the proposed architecture provides a transferable foundation for designing decentralized agro-industrial ecosystems capable of supporting sustainable rural industrialization across the Global South.

7. Policy and Development Implications

The proposed framework aligns closely with international priorities relating to sustainable energy, food security, climate resilience, and inclusive economic development. Rather than promoting isolated renewable energy projects, it advocates integrated rural development through decentralized agro-industrial ecosystems powered by agrivoltaic infrastructure.

The framework provides a practical basis for national governments, development agencies, multilateral organizations, and private investors seeking scalable solutions that simultaneously enhance agricultural productivity, expand energy access, strengthen local institutions, and create employment opportunities. Its modular structure also facilitates adaptation to diverse geographical, institutional, and socio-economic contexts throughout Sub-Saharan Africa and other regions of the Global South.

8. Conclusion

This study presents a governance-embedded, competence-driven socio-technical systems architecture that reconceptualizes agrivoltaics as a platform for decentralized agro-industrial development rather than solely as a renewable energy technology. By integrating biomimetic intelligence, agrivoltaic energy infrastructure, agricultural production, community co-development, governance, engineering competence infrastructure, and adaptive resilience within a unified layered framework, the study establishes a comprehensive systems engineering model for sustainable rural transformation.

The proposed architecture demonstrates that resilient rural development emerges not from technological innovation alone but from coordinated interactions among energy systems, institutional structures, human capability, community participation, and adaptive governance. Through its mathematical formulations, layered organization, and illustrative Nigerian application, the framework provides both a theoretical foundation and a practical blueprint for future system modelling, digital twin development, optimization, and large-scale implementation.

Beyond agrivoltaics, the proposed framework contributes a transferable methodology for designing integrated socio-technical infrastructures capable of supporting sustainable industrialization and community resilience across rapidly developing regions of the Global South.

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