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COMPETENCE INFRASTRUCTURE AND COMMUNITY CO-DEVELOPMENT AS AN INTEGRABLE ENGINEERING SUBSYSTEM: A BRIDGING CONSTRUCT FOR SOCIO-TECHNICAL RENEWABLE ENERGY SYSTEM ARCHITECTURES

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Abstract
Engineering system performance, particularly in decentralized renewable energy contexts, is increasingly shaped by factors that extend beyond technological configuration. Among these, competence has emerged as a critical determinant of system reliability, scalability, and long-term sustainability. Concurrently, growing evidence shows that community participation, local ownership structures, and decentralized governance mechanisms significantly influence infrastructure performance and resilience. In many deployment contexts, these human and institutional dimensions interact directly with competence development processes, shaping how systems are installed, maintained, and adapted over time. This communication consolidates the architectural representation and variable formulation of competence infrastructure as an integral engineering subsystem. Rather than treating competence as an external or contextual factor, the study reiterates it as a structured subsystem with defined components and measurable outputs that can be incorporated directly into system-level modeling. It further iterates how competence infrastructure's architectural structure can integrate with functional representation to enable competence to be expressed both as a subsystem layer and as a state variable influencing system performance. The communication also situates competence infrastructure within broader community development processes, where participation, co-management, and local knowledge systems play active roles in capability generation and system sustainability. By bridging subsystem architecture and variable formulation, it provides a basis for embedding competence infrastructure within multi-layer socio-technical system architectures. This communication provides a citable bridge between foundational framework and empirical work currently under review and the architecture and system-level integration paper, "A Multi-Layer Biomimetic Socio-Technical Architecture for PV and Agrivoltaic Systems: Integrating Competence Infrastructure and Community Co-Development in the Global South."

Keywords: *Competence infrastructure, Systems engineering, Socio-technical systems; Community co-development, Renewable energy deployment, Photovoltaic systems, Community-based renewable energy, Engineering subsystem*

Introduction

Systems are often described in terms of hardware, operational processes, and control mechanisms. These elements are undeniably central, yet they do not fully explain why some systems perform reliably in practice while others struggle despite adequate technical design and environmental factors. In many real-world deployments, especially in decentralized renewable energy systems, the difference frequently lies in something less visible but equally consequential: the capability of the people interacting with the system, and the communities, and of course, the environment within which those systems are embedded.

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 (Geels, 2019; Sovacool *et al*., 2019; Lesala and Mukumba, 2025).

This observation has become increasingly prominent in recent energy transition literature, which emphasizes that technical infrastructure alone does not guarantee sustainable performance without corresponding human and institutional capacity. As Geels (2019) explains, energy systems operate as socio-technical constructs in which technological, institutional, environmental, and human factors are tightly interwoven. In practice, systems deployed without adequate competence structures or community integration often exhibit reduced reliability, delayed maintenance, and limited long-term adoption. Empirical evidence across decentralized energy deployments further shows that system underperformance often arises not from technological inadequacy but from insufficient workforce capability, weak maintenance ecosystems, and limited community integration (Fred *et al*., 2024; IRENA, 2022).

Equally important is the role of communities themselves. Community participation is not merely a social consideration but a functional determinant of infrastructure performance, influencing monitoring, maintenance responsiveness, and system protection. Studies have shown that participatory governance structures improve maintenance responsiveness, increase system resilience, and enhance long-term sustainability (Okojokwu-Idu, 2023). Local actors frequently serve as first responders, informal managers, and co-governors of infrastructure systems, particularly in environments where centralized institutional capacity is limited. In parallel, research in community energy systems demonstrates that participation, ownership, and local governance structures significantly influence infrastructure performance (Hanke and Guyet, 2023), while Pascaris *et al*. (2021) show that distributed energy systems perform more effectively when aligned with local socio-economic and governance contexts.

Despite this growing recognition, workforce competence and community participation are still rarely incorporated explicitly into engineering system design frameworks. They are typically treated as external enabling conditions rather than as integral components of system architecture. This separation limits the ability of engineering models to accurately capture deployment realities, especially in decentralized energy systems where human capability, local governance, and community ownership structures directly influence system outcomes.

At the same time, prior work has already addressed competence in two distinct but complementary ways: as an engineered infrastructure system defined through a conceptualized framework, and as a measurable variable demonstrated through quantitative validation. However, these contributions are currently undergoing publication and are therefore not yet available for formal citation. Meanwhile, a subsequent paper extends these insights into a multi-layer socio-technical architecture, requiring a formally citable construct that stabilizes competence infrastructure in a form suitable for system-level integration.

It is precisely this gap that necessitates the present short communication. The need is not for new theory, nor for revalidation, but for consolidation. Without such a bridge, the transition from foundational work to integrated system architecture risks appearing discontinuous or unsupported. The work therefore contributes not only to renewable energy deployment theory but also to environmental systems management through the integration of technical, institutional, and community dimensions of sustainability.

Research Aim and Justification

This communication is not intended to reproduce the conceptual framework development or empirical validation of competence infrastructure. Its role is deliberately narrower and more focused. It provides a concise, citable bridge that consolidates the conceptual framing and variable meaning of competence infrastructure for use in the parallel multi-layer socio-technical architecture paper.

The aim is therefore not to introduce a new concept, but to consolidate and clarify an existing one in a way that makes it operational within engineering system design. In doing so, the study reiterates competence infrastructure as both a structured subsystem and a measurable variable, enabling its integration into multi-layer socio-technical architectures. What is brought forward here is the minimum necessary articulation required to make competence infrastructure intelligible, transferable, and analytically compatible with higher-order system representations. What is deliberately left out are extended derivations, empirical datasets, and full methodological treatments that belong properly to the foundational papers.

In this sense, the communication functions less as a standalone contribution and more as a structural link. It enables the transition from isolated conceptual and empirical insights to integrated system-level application, ensuring continuity without duplication.

Materials and Methods

The present communication builds upon two companion studies that originated from the same doctoral research programme on competence infrastructure for renewable energy deployment within community-based implementation contexts. The first study established the conceptual systems engineering framework for competence infrastructure, whereas the second empirically examined competence infrastructure as a measurable determinant of photovoltaic deployment capability within community deployment environments. The third companion study, published alongside this communication, extends these preceding contributions by integrating competence infrastructure into a multi-layer socio-technical architecture for renewable energy deployment and community implementation. The present communication serves as the conceptual bridge between the foundational competence infrastructure studies and that systems-level architecture.

Accordingly, this communication employs a structured construct-consolidation procedure to synthesize and translate the principal findings of the companion studies into an independently defined systems engineering construct suitable for integration within higher-order socio-technical architectures. The procedure comprised four sequential stages: (i) identification of the structural and functional elements established in the preceding conceptual and empirical studies; (ii) extraction and harmonization of subsystem components, variables, and mathematical representations; (iii) reformulation of competence infrastructure as both an engineered subsystem and a measurable system variable; and (iv) abstraction of the consolidated construct into a concise, citable representation suitable for subsequent systems integration. This transparent and reproducible procedure documents the derivation of the consolidated construct while avoiding duplication of the detailed conceptual development and empirical analyses reported in the companion studies.

The consolidation process is intentionally selective. Only the structural and functional core of competence infrastructure is retained, whereas detailed methodological procedures, analytical derivations, and empirical results are excluded. Consequently, the construct is reformulated into a compact, transferable representation that preserves conceptual integrity while remaining independent of the originating studies and suitable for application within broader systems engineering contexts.

A central feature of this methodological approach is the repositioning of competence from an external contextual factor to an internal system element. This perspective is consistent with socio-technical systems theory, which recognizes system performance as an emergent property arising from interactions among technical, organizational, and human subsystems rather than from technical optimization alone (Sovacool *et al*., 2019). The construct is further expressed in a form compatible with integrated system architectures described in contemporary systems integration and energy policy literature (Chatzinikolaou and Vlados, 2025).

The resulting construct is therefore neither a summary nor a duplication of the companion studies. Rather, it constitutes a systematic translation of their conceptual and analytical foundations into a higher level of systems abstraction, enabling competence infrastructure to function as an independently defined subsystem for subsequent integration within comprehensive socio-technical models of renewable energy deployment.

Results

Architectural and Variable Representation

From a systems engineering standpoint, competence infrastructure satisfies the criteria of a subsystem with identifiable components, defined functions, and observable outputs. At a structural level, it can be represented through interacting functional elements including simulation environments, procedural training systems, diagnostic capability development, and feedback processes. These elements collectively form a layered architecture through which competence is progressively developed, moving from familiarity to operational capability and ultimately to adaptive expertise.

At the same time, integration into engineering systems requires that competence be expressed as a variable. This is captured in the functional form:

$$C = f(S,P,D,F) \quad (1)$$

where competence C is generated as an output of structured processes, governed by a function f of interactive subsystems including simulation infrastructure S, procedural training infrastructure P, diagnostic training infrastructure D, feedback infrastructure F. This formulation enables competence to be incorporated into system-level models and linked directly to performance outcomes, consistent with broader modeling approaches in renewable energy systems (Weselek *et al*., 2021).

In dynamic terms, competence evolves cumulatively:

$$C_i(t+1) = C_i(t) + \alpha S_i(t) + \beta P_i(t) + \gamma D_i(t) + \delta F_i(t) \quad (2)$$

Where i indexes the competence dimension (installation, procedural, diagnostic), t denotes the time step or training iteration, and α (alpha), β (beta), γ (gamma), and δ (delta) represent the respective conversion efficiency coefficients of the simulation, procedural, diagnostic, and feedback subsystems in generating workforce competence. This representation reflects the adaptive nature of competence development and accommodates contributions from both formal training systems and community-based learning processes.

Engineering deployment capability is expressed as a function of competence:

$$EDC = f(C) \quad (3)$$

Where EDC denotes Engineering Deployment Capability. This relationship highlights the direct linkage between workforce capability and system performance, a connection reinforced by empirical findings on system reliability and maintenance outcomes (Fred *et al*., 2024). Within broader socio-technical systems, this relationship extends to include interactions with technological performance, governance structures, and adaptive feedback processes.

Discussion

Consolidated Conceptual Positioning of Competence Infrastructure

Competence, in everyday terms, is often understood as a characteristic of individuals. It includes skills, knowledge, and experience accumulated over time. From an engineering perspective, however, this view is incomplete, because competence does not emerge spontaneously. It is produced, shaped, and reinforced through structured processes that operate within institutional and community contexts. When viewed through this lens, competence begins to resemble infrastructure.

Competence infrastructure can therefore be understood as the set of organized systems responsible for generating and sustaining workforce capability. It includes training environments, simulation systems, procedural learning structures, diagnostic development mechanisms, and feedback processes. Importantly, these processes do not occur in isolation from social systems. They are embedded within communities, shaped by participation patterns, and influenced by local governance structures, a relationship also reflected in workforce development strategies for energy transitions (Republic of Ghana and ILO, 2021).

Community participation plays a critical role in this process. Participatory training environments, peer learning systems, and community-based knowledge exchange mechanisms contribute directly to competence generation. Evidence from renewable energy deployments shows that systems supported by active community engagement tend to exhibit stronger maintenance cultures, higher system uptime, and improved long-term sustainability. Similar patterns are observed in integrated energy systems research, where socio-technical alignment enhances system performance (Favi *et al*., 2024).

Ownership and management structures further reinforce this relationship. Where communities have a stake in system ownership, whether through cooperative models, shared governance, or localized management frameworks, there is often a stronger incentive to develop and sustain competence. This aligns with broader findings in community energy research, where local ownership and participation are associated with increased system resilience and acceptance.

This shift in perspective has important implications. Once competence is treated as infrastructure, and once that infrastructure is understood as socially embedded, it becomes possible to describe its structure, define its components, and analyze its performance using the same principles applied to other engineering subsystems. More importantly, it allows competence to be brought inside the system boundary, not only as a technical subsystem but as a socio-technical construct shaped by human interaction, institutional design, and community agency.

Integration Relevance Within Socio-Technical System Architectures

The integrability of competence infrastructure becomes most evident in multi-layer socio-technical architectures, where system performance emerges from the interaction of technological, human, and institutional domains. Within such architectures, competence infrastructure serves as a linking mechanism, connecting technical systems with human capability while simultaneously enabling community participation in system operation and management.

This dual role is particularly important in decentralized energy systems. Local actors often take on responsibilities for installation, maintenance, monitoring, and decision-making, especially in environments where centralized institutional capacity is limited. Community co-development processes further strengthen this integration, as participatory governance structures and shared ownership models create pathways through which competence is both developed and applied.

Without this integration, systems may perform well in controlled conditions but struggle in real-world environments. With it, systems become more adaptable, more resilient, and more capable of sustaining performance over time.

Relevance to the Parallel Architecture Paper

The necessity of this communication becomes most apparent when viewed alongside its companion paper. That paper advances a multi-layer socio-technical architecture in which competence infrastructure functions simultaneously as a subsystem, and a variable. Without a formally articulated bridge, these roles would lack a citable foundation. This communication resolves that issue by providing a coherent and independent representation of competence infrastructure that can be directly referenced. It ensures that the construct can be understood without reliance on prior work that are not yet citable, and integrated without conceptual discontinuity. In this sense, the present work does not stand alone. It operates in deliberate relation to the companion paper, enabling its conceptual continuity while maintaining academic independence.

Conclusion

This communication consolidates competence infrastructure into a form that is both architecturally defined and analytically integrable. By reiterating competence as both an engineered subsystem and a measurable variable, it provides a coherent basis for its incorporation into multi-layer socio-technical system architectures. The inclusion of community development dimensions; participation, ownership, and management, extends this construct beyond purely technical considerations. It recognizes that competence is not only generated through structured training systems but also through social interaction, institutional processes, and community engagement. Rather than duplicating the companion studies, this communication provides an independently citable systems engineering construct that enables competence infrastructure to be incorporated consistently into higher-order socio-technical architectures.

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