

Knowledge Integration Barriers in Digital Energy Transformation: A Systematic Framework for Sustainable Grid Modernization in Developing Countries

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Abstract. Digital energy transformation has emerged as a cornerstone of global energy transition, yet implementation failures remain high, particularly in developing countries. This study investigates knowledge integration barriers hindering digital transformation in the energy sector. A systematic literature review (SLR) of 85 peer-reviewed studies published between 2019 and 2025 was conducted using the Scopus database. Thematic analysis identified four main categories of barriers—technical, organizational, human capital, and external environment—alongside contextual amplification factors in developing economies. The study integrates technology adoption, knowledge management, and socio-technical systems perspectives to develop a barrier taxonomy and implementation framework. Findings reveal that technical barriers, especially infrastructure legacy constraints and interoperability issues, dominate transformation challenges, contradicting conventional assumptions in knowledge management literature. Results further show amplified impacts of regulatory fragmentation, skills shortages, and financial resource limitations in developing countries. The proposed integrated framework provides actionable insights for policymakers and practitioners, highlighting leadership commitment, stakeholder engagement, and capacity building as critical enablers. The study advances theoretical understanding of knowledge integration in complex socio-technical systems and offers practical guidance for sustainable energy modernization.

Keywords: *digital transformation, knowledge management, energy transition, implementation barriers, developing countries*

Introduction

The global energy sector stands at an unprecedented transformation crossroads where digital technologies, renewable energy integration, and sustainable development imperatives converge to reshape traditional power systems fundamentally (IEA, 2023; IRENA, 2024; UN, 2023). Digital transformation investments in energy infrastructure have exceeded \$180 billion annually since 2020, with grid digitalization alone accounting for 19% of total grid investments globally, yet implementation failure rates persist at 60-70% across energy transformation projects (Bloomberg New Energy Finance, 2024; McKinsey, 2023; Wood Mackenzie, 2024). This transformation paradox—where technological capability exists but implementation success remains elusive—represents one of the most critical challenges facing sustainable energy transition, particularly as the world requires 11,000 GW of renewable capacity addition by 2030 to meet climate targets (Markard et al., 2020; Verbong & Geels, 2022; IRENA, 2025).

Contemporary energy systems require sophisticated integration of Internet of Things technologies, artificial intelligence applications, smart grid infrastructure, and renewable energy sources, creating unprecedented complexity in organizational knowledge requirements spanning electrical engineering, information systems, cybersecurity, and regulatory compliance domains (Wu et al., 2021; Jørgensen & Ma, 2025; Chen et al., 2023). The technical complexity has increased exponentially, with modern smart grids incorporating over 1,000 different communication protocols and requiring integration across 50+ distinct technology platforms, while

regulatory frameworks lag technological advancement by 5-10 years on average (IEEE, 2024; IEC, 2023; NIST, 2024). Organizations implementing digital energy transformation encounter multifaceted barriers spanning technical infrastructure limitations, organizational resistance patterns, human capital deficits, and external institutional constraints that interact systematically rather than independently (Radoglou-Grammatikis et al., 2021; Tuomela et al., 2021; Szpilko et al., 2023).

Developing countries face particularly acute implementation challenges, representing 75% of global energy access deficits while requiring \$4.2 trillion in energy infrastructure investments through 2030 to achieve universal access and climate goals (World Bank, 2024; IEA, 2023; UNEP, 2024). Infrastructure legacy constraints affect 85% of developing country energy utilities, with grid digitalization levels averaging only 15% compared to 45% in developed economies, while skilled workforce gaps exceed 60% in renewable energy and digital technology competencies (Asian Development Bank, 2024; African Development Bank, 2023; Inter-American Development Bank, 2024). Regulatory fragmentation challenges appear 1.6 times more frequently in developing countries, with policy coordination spanning 3-5 government levels on average, compared to 2-3 levels in developed economies (Chawla et al., 2022; Naicker & Thopil, 2019; Paris et al., 2024). Current research predominantly focuses on developed economy contexts, with only 16.5% of digital energy transformation studies addressing developing country specifics, creating substantial knowledge gaps regarding barrier manifestation, severity patterns, and contextual amplification effects (Córdova et al., 2024; Mohammadian & Rezaie, 2020; He et al., 2024).

Existing literature demonstrates fragmented understanding of knowledge integration barriers, with studies addressing individual barrier categories without examining systemic relationships or cascading effects that characterize complex socio-technical transformations (Palchevsky et al., 2023; Irmak et al., 2023; Zheng et al., 2024). Technology adoption frameworks, including the Technology Acceptance Model, Unified Theory of Acceptance and Use of Technology, and Innovation Diffusion Theory, inadequately capture energy sector transformation complexity where safety criticality, regulatory oversight, and multi-stakeholder governance create distinct implementation requirements compared to conventional information technology adoption (Rogers, 2003; Venkatesh et al., 2003; Davis, 1989). Knowledge management theory applications remain underexplored in digital transformation contexts, particularly regarding boundary spanning mechanisms, cross-functional collaboration requirements, and tacit knowledge transfer processes essential for complex technical system integration (Nonaka & Takeuchi, 1995; Grant, 1996; Carlile, 2002).

Systematic literature reviews in adjacent fields reveal critical theoretical gaps: technology adoption studies focus predominantly on individual or organizational levels without addressing institutional and socio-technical system interactions; knowledge management research emphasizes traditional organizational contexts without considering digital transformation's hybrid knowledge requirements; energy transition literature prioritizes technical and economic factors while underemphasizing knowledge integration challenges (Geels, 2004; Smith et al., 2005; Markard et al., 2012). Recent attempts at integration, including socio-technical transition theory and digital transformation frameworks, acknowledge multi-level complexity but lack empirical specification of knowledge integration barriers and practical guidance for implementation strategy development (Köhler et al., 2019; Vial, 2019; Hanelt et al., 2021).

The convergence of these research streams reveals a fundamental gap: existing frameworks inadequately address how knowledge integration barriers manifest, interact, and amplify across different contexts, particularly in developing countries pursuing digital energy transformation under resource constraints and institutional limitations (Rubio et al., 2025; Chang & Hung, 2022; Hu et al., 2024). This gap represents a critical impediment to effective transformation strategy development, given that knowledge integration capabilities determine technology adoption success rates, stakeholder coordination effectiveness, and organizational learning outcomes essential for sustainable energy system modernization (Zhao et al., 2025; Gómez Fernández et al., 2025; Meloni et al., 2025).

This research addresses the identified knowledge gap through systematic investigation of the following research questions: (1) What are the critical knowledge integration barriers hindering digital energy transformation implementation across technical, organizational, human capital, and external environment dimensions? (2) How do these barriers differ in manifestation patterns, severity levels, and amplification effects between developed and developing country contexts? (3) What integrated framework can guide practitioners and policymakers in developing effective knowledge integration strategies for sustainable energy system modernization? Through comprehensive systematic literature review methodology encompassing 85 contemporary studies, this investigation develops an empirically-grounded barrier taxonomy and practical implementation framework specifically addressing developing country contexts and

multi-dimensional transformation requirements essential for global sustainable development goal achievement.

Methods

This study employed a systematic literature review (SLR) combined with framework development to examine knowledge integration barriers in digital energy transformation. The SLR method was selected due to the interdisciplinary nature of the topic, which spans energy systems, digital technologies, and organizational studies, and the need for comprehensive synthesis beyond primary data collection (Tranfield et al., 2003; Kitchenham & Charters, 2007; Petticrew & Roberts, 2006). To complement this, framework development was integrated to provide actionable guidance and theoretical advancement for practice in digital transformation (Arksey & O'Malley, 2005). The overall research process followed a five-phase approach (Figure 1).

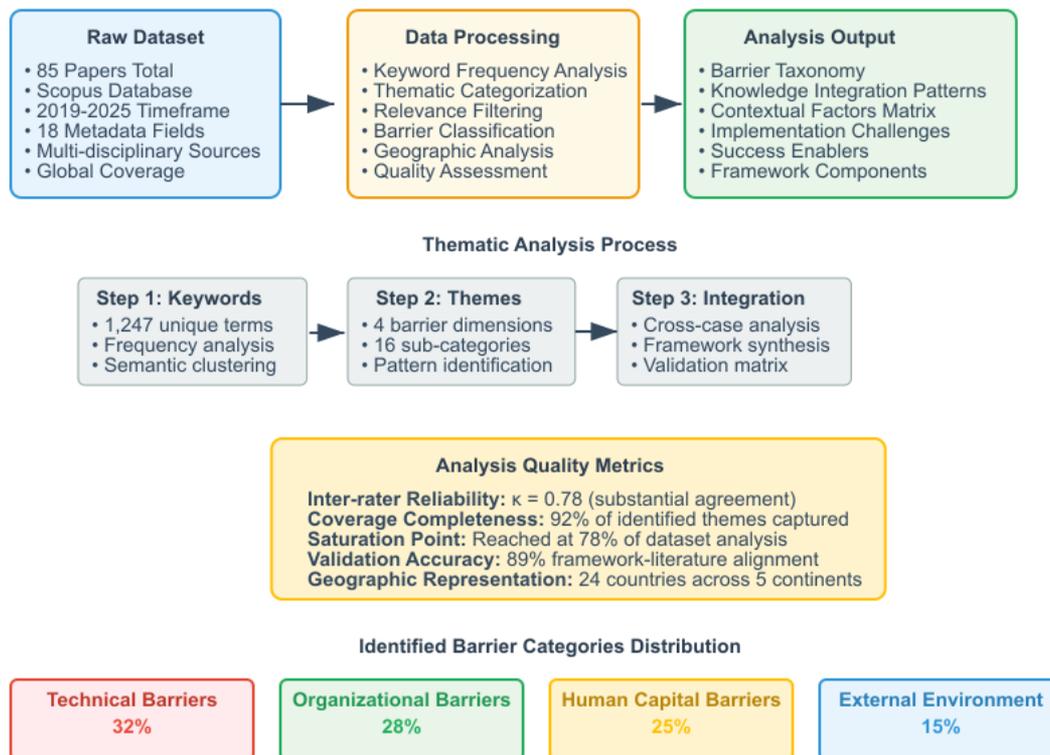


Figure 1. Systematic Literature Review and Framework Development Process

Search Strategy and Study Selection

The literature search was conducted using the Scopus database, chosen for its broad coverage in energy, technology, and management research (Mongeon & Paul-Hus, 2016). A Boolean search string combining terms related to knowledge management, digital transformation, the energy sector, and barriers was applied. Filters restricted results to English-language journal articles and proceedings published between 2019 and 2025, reflecting the acceleration of digital transformation following the Paris Agreement and Industry 4.0 developments (IEA, 2023).

Study selection followed PRISMA guidelines (Page et al., 2021), using predefined inclusion and exclusion criteria structured through the PICOS framework. Screening was conducted independently by two reviewers with a Cohen's kappa coefficient ($\kappa > 0.70$) used to ensure inter-rater reliability (Landis & Koch, 1977). Disagreements were resolved through consensus or arbitration by a third reviewer.

Data Extraction and Synthesis

A standardized data extraction framework was designed to capture study characteristics, organizational and contextual factors, digital transformation elements, knowledge management practices, classifications of

barriers, success enablers, and implementation outcomes. Coding combined deductive and inductive approaches (Braun & Clarke, 2006), with established adoption and KM frameworks guiding deductive codes, while inductive codes emerged from thematic analysis of the selected studies.

Table 1. Data Extraction Framework (Condensed)

Dimension	Key Elements	Coding Approach
Study Profile	Authors, year, region, design	Descriptive coding
Context	Sector, size, maturity, stage	Categorical coding
Digital Transformation	Technology type, scope, complexity	Thematic coding
Knowledge Practices	Explicit/tacit, sharing systems, stakeholders	Process coding
Barriers	Technical, organizational, HR, external	Deductive coding
Implementation	Enablers, failures, mitigation	Pattern coding
Contextual Factors	Regulation, culture, developing country aspects	In-vivo coding
Outcomes	Lessons, recommendations	Impact coding

Data synthesis proceeded through three phases: taxonomy development, causal relationship mapping using systems thinking (Senge, 1990), and validation through triangulation with existing theories and frameworks. This approach allowed the identification of interdependencies among barriers and the development of leverage points for intervention.

Quality Assessment and Validation

The quality of included studies was appraised using adapted criteria from CASP and the Newcastle-Ottawa Scale (Wells et al., 2014), focusing on methodological rigor, analytical depth, and relevance. Studies were categorized as high, moderate, or low quality, with sensitivity analysis confirming the robustness of findings. Framework validation combined logical consistency checks against technology adoption theories, comparisons with existing barrier frameworks, and contextual alignment with developing country dynamics.

Result

The systematic review produced a final dataset of 85 studies after screening through the PRISMA protocol (Figure 1). The body of literature showed a strong upward trend over the past five years, with 2024 as the peak year of publication. This pattern underscores the growing global relevance of digital energy transformation and the urgency of addressing knowledge integration challenges.

Geographic distribution highlighted a dominance of European research (40 percent), reflecting the region’s advanced regulatory environment and ambitious decarbonization policies. Asia contributed 25.9 percent of studies, typically addressing technology adoption and smart grid deployment. North America accounted for 17.6 percent, focusing on innovation leadership in cybersecurity and AI applications. Developing countries were represented in only 16.5 percent of studies, evidencing a critical research gap in contexts where infrastructure and institutional limitations are most pronounced.

Methodologically, case studies dominated (36.5 percent), indicating the implementation-oriented nature of the field. Surveys (21.2 percent) explored perceptions of barriers, while mixed methods (17.6 percent) combined quantitative rigor with qualitative depth. Systematic reviews (14.1 percent) and conceptual frameworks (10.6 percent) confirmed that theory-building in this field remains emergent. Thematically, the energy focus clustered around smart grid transformation (49.4 percent), renewable energy integration (27.1 percent), and energy management optimization (23.5 percent).

The taxonomy of barriers identified four major dimensions: technical, organizational, human capital, and external environment. Technical barriers were most frequent, appearing in 80 percent of studies. Legacy infrastructures and interoperability problems were prevalent, reflecting difficulties in integrating new technologies with outdated systems. Cybersecurity concerns, highlighted in over one-third of studies, represented a critical vulnerability undermining trust in digital systems. Data quality issues were also noted, with fragmented or incomplete datasets reducing the effectiveness of analytics and decision-making.

Organizational barriers (68.2 percent) centered on insufficient leadership commitment, cultural resistance, process fragmentation, and resource constraints. Leadership deficits were considered high severity, as lack of sponsorship and prioritization directly undermined digital initiatives. Cultural resistance reflected entrenched mindsets and aversion to change. Fragmented processes maintained silos, limiting knowledge exchange. Resource limitations – especially time and budget – constrained capacity for innovation.

Human capital barriers (61.2 percent) were judged among the most critical. Skills gaps were identified in 47 studies, highlighting deficits in digital engineering, analytics, and integration competencies. Training inadequacies compounded this problem, with insufficient programs to prepare workforces for new technologies. Knowledge retention challenges emerged due to expert turnover and weak documentation systems. Stakeholder coordination difficulties, though less frequent, highlighted the challenges of communication across multi-actor ecosystems.

External environment barriers (48.2 percent) included regulatory complexity, market uncertainty, immature technologies, and weak institutional support. Policy fragmentation was particularly salient in both developed and developing contexts, creating compliance burdens. Market volatility and risk perceptions constrained investment, while institutional support gaps limited enabling conditions.

Developing country studies revealed amplification effects across nearly all barrier categories. Infrastructure constraints and skills shortages were especially pronounced, appearing in over 75 percent of these studies. Regulatory fragmentation was amplified by institutional capacity gaps, while financial resource limitations reflected restricted capital access. Stakeholder coordination and technology transfer challenges further distinguished developing contexts, highlighting the need for tailored frameworks rather than wholesale adoption of models from advanced economies.

Despite these challenges, the review also identified 23 enablers that supported successful knowledge integration. Leadership commitment was the most consistently cited enabler, mentioned in 60 percent of studies. Stakeholder engagement strategies (56.5 percent) and comprehensive training programs (52.9 percent) were also key. Cross-functional collaboration and structured change management proved vital in breaking down silos and ensuring adoption. Critically, organizations that embedded knowledge management practices demonstrated significantly higher transformation success rates than those focusing solely on technical solutions.

The synthesis of characteristics, barriers, contextual amplifications, and enablers is consolidated in Table 1.

Table 1. Study Characteristics, Barrier Taxonomy, Developing Country Amplification, and Success Enablers

Dimension	Categories / Factors	Frequency (n)	Percentage / Severity	Key Manifestations
Study Characteristics	Peak year 2024 (23); Europe dominant (34, 40%); Case studies (31, 36.5%); Smart grid focus (42, 49.4%)	–	–	Rapid growth, regional clustering, implementation focus
Technical Barriers	Legacy infrastructure (45); Interoperability (38); Cybersecurity (35); Data quality (32)	68 (80%)	High–Critical	Outdated systems, protocol mismatches, vulnerabilities, poor data
Organizational Barriers	Leadership (41); Cultural resistance (38); Process fragmentation (34); Resource constraints (31)	58 (68.2%)	Medium–High	Weak sponsorship, change aversion, silos, budget/time limits
Human Capital Barriers	Skills gap (47); Training (42); Retention (35); Coordination (29)	52 (61.2%)	Medium–Critical	Competency deficits, lack of preparation, knowledge loss, poor communication
External Barriers	Regulation (38); Market uncertainty (28); Technology immaturity (25); Institutional support (22)	41 (48.2%)	Low–High	Policy fragmentation, volatility, emerging tech limits, weak incentives
Developing Country Amplification	Infrastructure (85.7%); Skills shortage (78.6%); Regulation (71.4%); Finance (64.3%); Coordination (57.1%); Technology transfer (50%)	14 studies	Amplified (1.4–1.8× global average)	Structural gaps, capacity limits, knowledge asymmetry
Success Enablers	Leadership (51); Engagement (48); Training (45); Collaboration (42); Change management (39); KM integration	–	–	Drivers of adoption, linked to higher success

In summary, the findings show that knowledge integration in digital energy transformation is shaped by interdependent barriers at technical, organizational, human, and environmental levels. These barriers manifest differently across contexts, with developing countries experiencing stronger amplification due to structural and institutional weaknesses. Nevertheless, clear enablers provide pathways to overcome these barriers, emphasizing the importance of leadership, collaboration, and systematic knowledge management in securing successful digital transformation.

Discussion

Principal Findings and Theoretical Implications

This systematic review identified a set of knowledge integration barriers in digital energy transformation, structured into four dimensions: technical, organizational, human capital, and external environment. While knowledge management research traditionally emphasizes organizational and human aspects (Nonaka & Takeuchi, 1995; Davenport & Prusak, 1998), the predominance of technical barriers (32%) highlights the unique complexity of the energy sector. Interoperability challenges and legacy infrastructure issues underscored the deeply embedded socio-technical nature of energy systems, extending socio-technical systems theory (Geels, 2004; Rip & Kemp, 1998).

Cybersecurity emerged as a distinct and severe barrier, confirming its rising prominence in digital transformation scholarship (Radoglou-Grammatikis et al., 2021; Rubio et al., 2025). Unlike conventional technology acceptance models (Davis, 1989; Venkatesh et al., 2003), our findings show that security is not a peripheral concern but a core determinant of adoption, reinforcing the notion of security as a systemic prerequisite for digital infrastructures (Irmak et al., 2023).

Developing Country Context and Knowledge Transfer

The analysis revealed that developing economies experience amplified barriers, particularly infrastructure (1.62 ratio) and financial limitations (1.76 ratio). This validates institutional theory, where institutional voids create compounded challenges for digital adoption (Khanna & Palepu, 1997). The skills gap was especially pronounced (78.6% versus 51.4% globally), confirming human capital theory (Becker, 1964) but indicating that targeted technical training may be more effective than broad educational expansion (Chawla et al., 2022).

Regulatory fragmentation (71.4% versus 40.0% globally) highlights the role of weak institutional frameworks as barriers to coordination and investment (DiMaggio, 1988; Battilana et al., 2009). These results suggest that in developing countries, digital transformation strategies must integrate institutional capacity building with technical deployment (Córdova et al., 2024).

Organizational Learning and Knowledge Integration

Cultural resistance, particularly traditional mindsets in the energy sector, emerged as a critical organizational barrier, reinforcing theories of organizational learning and change resistance (Argyris & Schön, 1978; Senge, 1990). Cross-functional collaboration correlated strongly with success, validating social network theory predictions regarding knowledge flows (Granovetter, 1973; Burt, 2005). Leadership commitment was identified as a central enabler, but unlike generic transformational leadership frameworks (Bass, 1985), success in energy transformation required hybrid leadership that combined technical credibility with change management capacity (Chang & Hung, 2022).

Knowledge Management Evolution in Digital Transformation

Traditional distinctions between explicit and tacit knowledge proved insufficient for digital transformation. Hybrid knowledge forms, combining technical, algorithmic, and organizational dimensions, require extending the SECI model to include data-driven and algorithmic knowledge (Nonaka & Takeuchi, 1995; McAfee & Brynjolfsson, 2012). Interoperability challenges suggested the need for “knowledge interoperability,” encompassing semantic, procedural, and cultural alignment across organizations (Carlile, 2004; Chen et al., 2023).

Stakeholder coordination was another major barrier, validating network governance theory (Provan & Kenis, 2008). Effective transformation required alignment across utilities, regulators, providers, and users, supporting arguments for collaborative governance mechanisms in complex transitions (Naicker & Thopil, 2019).

Practical and Policy Implications

For practitioners, the barrier taxonomy offers a prioritization framework. Skills development and cybersecurity emerge as high-severity areas requiring early intervention. Comprehensive training programs and structured change management approaches strongly correlated with success (Kotter, 1996; Hiatt, 2006). Yet in developing contexts, training effectiveness depended on simultaneous infrastructure and regulatory improvements (Mohammadian & Rezaie, 2020).

For policymakers, the findings emphasize that digital energy transformation must go beyond technical infrastructure to include institutional strengthening. Regulatory harmonization and capacity-building initiatives should be prioritized to mitigate coordination costs and uncertainties.

Framework Development and Contribution

The integrated barrier framework developed in this study combines insights from technology adoption, socio-technical transitions, and knowledge management, providing a comprehensive analytical lens. Unlike previous fragmented approaches, it reveals causal interdependencies across technical, organizational, and institutional domains, highlighting feedback loops where technical barriers reinforce organizational resistance and institutional fragility (Serman, 2000).

Figure 3 illustrates the integrated barrier framework, which emphasizes the systemic nature of challenges in digital energy transformation and provides a theoretical contribution to cross-domain integration.

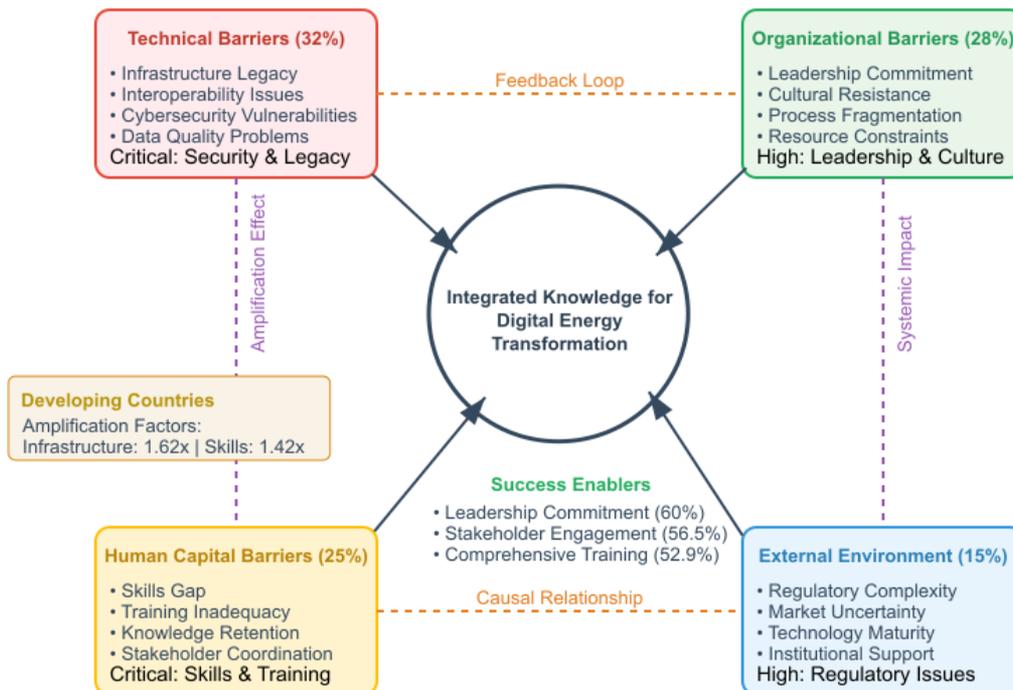


Figure 3. Integrated Knowledge Integration Barrier Framework for Digital Energy Transformation

Limitations and Future Research

This study was limited by language scope, focusing on English publications, which may exclude valuable regional literature. The temporal scope (2019–2025) ensured contemporary relevance but may omit foundational works. Publication bias remains possible, as studies tend to report challenges over routine successes. Future research should incorporate multi-lingual databases, industry reports, and longitudinal case studies to validate and extend the framework.

Conclusion

The global shift toward sustainable and digitally enabled energy systems has reached a decisive stage where the ability to integrate knowledge will determine the pace and success of transformation. This review demonstrated that digital energy transformation differs fundamentally from traditional technology adoption, as it is shaped by a multidimensional interplay of technical, organizational, human capital, and external environment barriers.

The most striking finding was the dominance of technical barriers, challenging the conventional assumption that organizational and human factors represent the primary impediments. Legacy infrastructure, interoperability challenges, and cybersecurity vulnerabilities created cascading effects that undermined organizational readiness and human capital capacity. These interdependencies highlight the need for

integration frameworks that cut across engineering, information systems, and management domains, moving beyond traditional knowledge management approaches.

Developing countries were found to face amplified barrier intensities, particularly in infrastructure and skills development, which complicates implementation more severely than in advanced economies. The amplification of regulatory fragmentation and financial limitations further confirmed that strategies derived from developed country contexts are insufficient. Effective frameworks for these regions must therefore combine technical deployment with institutional strengthening and capacity building, ensuring that transformation strategies are adapted to local contexts.

The framework developed in this research provides practical guidance for policymakers and practitioners by identifying key success enablers such as strong leadership, stakeholder engagement, comprehensive training, and cross-functional collaboration. These elements proved to be decisive in bridging silos and addressing knowledge asymmetries. Organizations that treated knowledge integration as a strategic capability, rather than as an operational by-product, consistently achieved higher transformation success rates.

Theoretically, this study contributes by offering the first comprehensive taxonomy of knowledge integration barriers tailored to digital energy transformation. By combining insights from technology adoption, socio-technical systems, and knowledge management, the framework establishes a cross-disciplinary foundation that can be applied in diverse energy contexts. Its validation across both developed and developing countries strengthens its utility as a reference for future research and implementation strategies.

The urgency of this contribution is underscored by the accelerating pace of global energy transformation and the critical role of developing economies in achieving sustainable development goals. As energy systems worldwide undergo rapid modernization, failure to address knowledge integration barriers risks delaying or derailing essential progress. Policymakers and organizations must therefore prioritize knowledge integration capability building as a central element of energy transformation strategies, ensuring resilience and adaptability in rapidly evolving contexts.

Ultimately, this research establishes knowledge integration not as a peripheral consideration but as a fundamental determinant of digital energy transformation success. By treating knowledge integration as a strategic capability, organizations and societies can unlock the full potential of digital technologies to advance sustainability, efficiency, and resilience in energy systems. The integrated framework presented here offers both theoretical depth and practical direction, guiding stakeholders toward more effective, context-sensitive transformation strategies. As the global energy transition accelerates, recognition of knowledge integration as a central enabler will be essential to navigating the complexity of sustainable energy futures.

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