
Development Of An Integrated Lifecycle Decision Framework For Renewable Energy Projects In Remote Power Systems: The RELiS Concept

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Abstract

Renewable-energy technology selection in remote power systems is a lifecycle decision rather than a one-time feasibility choice. Although established asset-management governance can prescribe whole-lifecycle management, risk-informed decision-making, asset information management, and continuous improvement, project-level decisions still require a structured mechanism for translating evidence that emerges at different lifecycle stages into early technology evaluation. This study develops RELiS (Renewable Energy Lifecycle-integrated System), an integrated decision framework for renewable-energy projects in remote power systems. A design-science research approach was combined with qualitative document analysis, directed qualitative content analysis, and embedded cross-case comparison. The evidence base comprised pseudonymized strategic asset-management and generation operation-and-maintenance governance documents, together with engineering, manufacturing, implementation, failure-investigation, and cost records from an Indonesian state-owned electricity utility (the study organization). Integrated analysis of asset-management governance, feasibility requirements, and cross-lifecycle case evidence identified seven decision domains: system, resource and business-value fit; technical and engineering readiness; lifecycle and cost readiness; manufacturing and supply-chain readiness; maintainability and reliability readiness; risk, safety and resilience; and information, knowledge and lifecycle learning. The cases reveal downstream considerations—such as material conformity, drawing completeness, spare-part and supplier constraints, field-condition changes, component wear, instrumentation deficiencies, and missing technical documentation—that can be material to upstream technology evaluation. RELiS therefore complements, rather than replaces, feasibility studies and asset-management governance by providing an evidence-traceable project-level decision architecture. The current study offers a documentary demonstration of the framework; external expert validation, quantitative weighting, multi-criteria ranking, lifecycle-cost modeling, and sensitivity analysis remain future research stages.

Keywords: *Renewable Energy; Lifecycle Decision Support; Asset Management; Maintainability; Supply Chain; Small Hydropower; Remote Power Systems; Design Science*

INTRODUCTION

The development of renewable energy in remote and isolated power systems is changing the nature of technology selection decisions. In conditions of logistical constraints, uneven local technical capabilities, long spare parts lead times, and the need to maintain generating assets operational with limited redundancy, technologies that are technically feasible at the design stage may not necessarily deliver optimal value throughout their life cycle. Therefore, technology selection needs to consider not only resource availability and initial investment, but also manufacturability, supply chain resilience, ease of maintenance, operational capabilities, information quality, and the organization's ability to leverage lessons learned from asset performance after the technology is implemented. Operationally, this study uses the term remote power systems for contexts in which lifecycle decisions are materially constrained by one or more of the following: geographic or logistical access, limited local technical capability or specialist availability, constrained redundancy or recovery options, long spare-part or supplier lead times, and restricted maintenance support; this definition is specified further in the Methods section.

The renewable energy planning literature has demonstrated that technology selection is a multidimensional issue involving multiple objectives and criteria. Multi-criteria decision-making (MCDM) approaches are widely used to balance economic, technical,

environmental, and social aspects, while life-cycle approaches attempt to account for consequences beyond the initial capital outlay (Ghasempour et al., 2019; Karunathilake et al., 2019; Sitorus & Brito-Parada, 2022). Recent studies on distributed renewable energy systems also show variation in criteria selection and weighting methods, with economic and technical dimensions remaining dominant and context sensitivity remaining a key concern (Gallozzi et al., 2026). However, these approaches are primarily used to compare and rank alternative technologies, while evidence relevant to technology decisions can emerge after the initial decision is made, namely during the engineering, manufacturing, construction, operation, maintenance, and failure investigation stages.

These issues are becoming increasingly important in the management of asset-intensive power generation assets. Contemporary asset management principles emphasize value creation throughout the asset lifecycle, risk-based decision-making, alignment of asset decisions with organizational objectives, information quality, and continuous improvement (ISO, 2024a, 2024b; GFMAM, 2024; IAM, 2024). Research on strategic asset planning also indicates that decisions made today need to consider conditions that may change throughout the asset's lifetime (Elsawah et al., 2019). However, asset management principles and project feasibility studies serve different purposes. Asset management systems provide governance and value creation principles, while feasibility studies are used to determine project viability. This situation suggests the need for a project-level decision-making layer that can link evidence generated at various lifecycle stages with early technology evaluation.

These issues are evident in the documentation that serves as the empirical basis for research within an Indonesian state-owned electricity utility (hereafter, the study organization). The documents analyzed cover multiple lifecycle stages of small-scale hydropower projects and related operational activities. One case includes technical discussions regarding turbine configurations, manufacturing options, installation drawings, wiring diagrams, spare parts lists, and operation and maintenance manuals from the engineering stage. Another case highlights manufacturing and supply chain risks related to material conformity, supplier delays, assembly control, quality inspections, and rework. A further case highlights field conditions that led to implementation changes and contract amendments. Operational investigation documentation, meanwhile, provides evidence of mechanical wear, coupling and bearing issues, hydraulic and control system deficiencies, instrumentation issues, and the absence of wiring diagrams. Overall, this evidence demonstrates that experience and information generated downstream are relevant to upstream technology decisions, but a structured mechanism is required to retrieve and use this evidence in subsequent technology evaluations.

The research gap in this context does not lie in the absence of lifecycle management within the study organization. Within the coded internal corpus, AM-01 (2025; Table 1) defines asset management as a coordinated, cross-functional activity that balances costs, risks, opportunities, benefits, and performance, and requires lifecycle management, stakeholder satisfaction, risk integration, information quality, and continuous improvement. The coded generation operation-and-maintenance source OM-01 (2023; Table 1) divides the lifecycle into acquire, operate, maintain, and disposal stages, with operations management, efficiency, work planning and control, outage, reliability, supply chain, lifecycle and cost, fuel handling, and process safety as operational pillars supported by risk, information, human capabilities, quality, health, safety, and the environment. The question that remains to be answered is how these principles are translated into a project-level technology evaluation structure that explicitly integrates evidence from engineering, manufacturing, supply chain, installation, operation, maintenance, and failure investigation. Aspects such as access to spare parts, completeness of documentation, condition-monitoring capabilities, local repair

capability, supplier dependency, and learning from failures need to be explored as part of technology evaluation rather than stored only after decisions have been made.

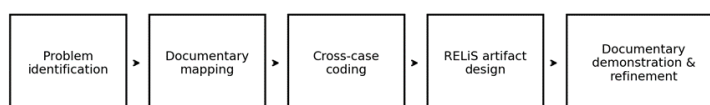
Based on these issues, this study aims to develop RELiS (Renewable Energy Lifecycle-integrated System) as a traceable, evidence-based evaluation framework for renewable energy technologies that complements existing feasibility studies and asset management processes. The urgency of this study lies in the need to provide a project-level decision-making mechanism capable of linking information across the lifecycle, particularly in remote power systems facing limitations in logistics, maintainability, documentation, and supply chain dependencies. The novelty of this study lies in the development of a RELiS architecture that integrates evidence across lifecycle stages into seven evaluation domains as a basis for technology decision-making. This study focuses on the development of the criteria architecture and evidence traceability, while the weighting and ranking of alternatives are deferred until expert validation is conducted. Thus, this study does not claim that RELiS has improved project costs, reliability, or duration, but rather provides a conceptual and documentary basis that can be tested through subsequent empirical research.

RESEARCH METHODS

Research design

The study uses design science research (DSR) because its principal output is an artifact: a structured decision framework intended to address a practical problem. Design science develops knowledge through the construction and evaluation of purposeful artifacts (Hevner et al., 2004). The DSR process was organized around problem identification, definition of design objectives, artifact development, documentary demonstration, and refinement, consistent with the staged logic described by Peffers et al. (2007). In the present study, artifact evaluation is limited to documentary demonstration and internal consistency checking against the embedded cross-lifecycle case evidence; external expert validation, quantitative weighting, lifecycle-cost modeling, and sensitivity testing are reserved for subsequent research. Internal consistency was assessed using four design checks: (1) traceability of each RELiS domain to documentary evidence; (2) cross-lifecycle support where available; (3) coherence among domains with limited conceptual overlap; and (4) non-duplication with feasibility assessment, asset-management governance, and generation O&M processes.

DSR was combined with qualitative document analysis because the relevant evidence is embedded in policies, procedures, engineering records, risk registers, meeting records, investigation reports, quality-control documents, and financial records. Document analysis provides a systematic approach to evaluating documentary material as qualitative data (Bowen, 2009). Directed qualitative content analysis was used to begin with sensitizing concepts from asset-management and renewable-energy decision literature while allowing additional categories to emerge from the cases (Hsieh & Shannon, 2005).



Design Science Research + qualitative document analysis + embedded multiple-case evidence

Figure 1. Research design used to develop the RELiS framework.

Study setting and pseudonymization

The study was conducted using an internal documentary corpus from an Indonesian state-owned electricity utility, referred to in the analytic text as the study organization. The

author's institutional affiliation is disclosed transparently on the title page and is not treated as pseudonymized. Pseudonymization is applied instead to the internal evidence corpus to reduce disclosure of operational and commercially sensitive information. Internal documents, organizational units, projects, locations, contractors, suppliers, personnel, contract numbers, and policy or record identifiers are therefore represented using coded labels (for example, AM-01 and OM-01 for internal governance sources and Cases A–D for project evidence sets). This convention protects source-level confidentiality without implying that the author's employer affiliation is unidentifiable.

Pseudonymization does not imply that re-identification is impossible for a highly informed industry reader. Accordingly, the manuscript avoids original internal policy numbers, project locations, personnel names, vendor names, screenshots, coordinates, exact contractual identifiers, and exact commercially sensitive values. Public Indonesian laws and international standards remain cited in their original form because they are not confidential.

Operational definition and case selection

Within this study, remote power systems are operationally defined as electricity systems or projects in which lifecycle decisions are materially constrained by one or more of the following conditions: geographic or logistical access, limited local technical capability or specialist availability, constrained redundancy or recovery options, long spare-part or supplier lead times, and restricted maintenance support. The term is used as an analytical context rather than as a universal classification threshold. The selected cases were retained because their documentary records reflected one or more of these constraints, particularly logistics and supportability, specialist access, documentation and spare-part availability, or recovery limitations.

Cases A–D were selected purposively using criterion-based sampling. A case was included when (1) formal documentary evidence was available; (2) the evidence represented a distinct lifecycle position relevant to technology evaluation; (3) it contained decision-relevant technical, manufacturing, implementation, operational, maintenance, risk, supply-chain, information, or cost evidence; and (4) the set collectively enabled cross-lifecycle comparison. The selection was designed for analytic coverage rather than statistical representativeness, and no claim is made that the four cases constitute the full population of projects within the study organization.

Documentary corpus and source hierarchy

Table 1. Pseudonymized documentary corpus used in the study.

Code	Document set	Year / status	Role	Primary analytical contribution
AM-01	Corporate Asset Management Policy	2025	Normative baseline	Whole-life-cycle, value, risk, information, stakeholder requirements, improvement
OM-01	Generation O&M Governance Procedure	2023	Operational baseline	Acquire-operate-maintain-dispose; O&M pillars; lifecycle costs; feedback
FS-01	Small-hydropower feasibility assessment procedure	Withheld	Feasibility baseline	Early-stage technical, economic, environmental and implementation feasibility
CA-01	Case A engineering and project records	Withheld	Upstream case	Engineering choices, documentation, spares, interfaces and readiness
CC-01	Case C final report, risk register and inspection-test plan	Withheld	Manufacturing case	Material conformity, supplier delay, assembly, QC, rework
CD-01	Case D meeting and amendment records	Withheld	Implementation case	Emergent technical conditions, dependencies, tuning, amendments

Code	Document set	Year / status	Role	Primary analytical contribution
CB-01	Case B investigation and repair records	Withheld	Downstream case	Failure investigation, wear, controls, documentation, maintenance learning
CF-01	Related intervention cost records	Withheld	Cost illustration	Normalized material/service/overhead cost structure

Table 2. Source hierarchy used to control evidentiary weight.

Evidence tier	Source type	Use in analysis
Tier 1	Strategic policy / formal procedure	Normative requirements and governance baseline
Tier 2	Formal assignment, contract, Terms of Reference (TOR), final investigation/report, quality-assurance (QA) or inspection-and-test-plan (ITP) records, final cost record	Primary process, technical, and financial evidence
Tier 3	Official meeting records and amendment records	Primary process/change evidence
Tier 4	Working notes and contextual technical notes	Supporting contextual evidence only; not treated as primary or conclusive evidence

Analytical procedure

The analysis was conducted in four coding passes. First, each documentary excerpt was assigned a lifecycle-stage code: feasibility/planning, engineering, procurement/manufacturing, implementation/commissioning, operation, maintenance/failure, or disposal/renewal. Second, evidence was coded by decision theme: system fit, engineering, cost, supply chain, maintainability/reliability, risk/safety, and information/learning. Third, cross-case comparison was used to identify recurring decision requirements and stage-to-stage dependencies. Fourth, the requirements were consolidated into the RELiS domains, with explicit attention to avoiding duplication of existing feasibility or asset-management governance.

A chain-of-evidence matrix was maintained conceptually from source document to coded observation, RELiS domain, and design requirements. Contradictory evidence was retained. For example, existing governance already prescribes whole-lifecycle management; therefore, the framework is not presented as evidence that lifecycle governance is absent. Instead, empirical project records are used to demonstrate the need for a project-level translation mechanism.

Research trustworthiness and boundaries

Trustworthiness was strengthened through source triangulation across policy, formal project documents, investigation records, quality records, change records, and cost records. The analysis also differentiates between normative evidence (what should occur), process evidence (what was planned or discussed), and outcome evidence (what was observed during manufacture, implementation, operation, or investigation). Working notes were used only to support context and were not treated as conclusive evidence. Because the author has professional experience within the electricity sector, potential insider interpretive bias was mitigated through the source hierarchy, cross-source triangulation, retention of contradictory evidence, explicit separation of evidence types, and maintenance of a chain-of-evidence audit trail.

The present study is a framework-development and documentary-demonstration paper. It does not report expert validation, content-validity indices, AHP/TOPSIS weights, sensitivity analysis, or causal performance improvement. Those analyses require data that have not yet been collected. This boundary is intentional to avoid presenting proposed performance targets as empirical results.

RESULTS AND DISCUSSION

Documentary Findings

Governance baseline: lifecycle principles already exist

AM-01, the coded internal asset-management policy summarized in Table 1, establishes a broad strategic baseline for the study organization. The source treats asset management as a coordinated activity across organizational units and explicitly balances costs, risks, opportunities, benefits, and performance. It requires lifecycle management to realize business value; data-, information-, and risk-based planning; integration with finance, human resources, information systems, logistics, and operations; stakeholder requirements management; information quality; and continuous improvement. Importantly, it also requires documentation of actual implementation against budget, time, initial plans, risk events, mitigation, and consequences. This means that RELiS cannot claim novelty solely by introducing lifecycle thinking.

OM-01, the coded internal generation O&M governance source summarized in Table 1, translates the asset-management philosophy into generation O&M. Its lifecycle model is acquire-operate-maintain-dispose. Acquire includes design, modification, procurement, construction, and commissioning; Maintain includes inspection, condition monitoring, testing, refurbishment, and life extension. The source also includes supply-chain management and lifecycle-and-cost management as O&M pillars and requires feedback from operations and improvement activities into subsequent planning. These provisions establish a strong organizational rationale for using downstream evidence in upstream decisions.

The implication for framework design is that RELiS should function as an operational decision-support artifact within—not outside—the existing asset-management ecosystem. It should structure evidence and decision rationale at the technology/project interface, while preserving the roles of feasibility studies, formal asset-management plans, O&M processes, risk management, and corporate investment governance.

Case A: engineering and documentation readiness

Case A represents an upstream small-hydropower engineering and manufacturing context. Project records show that technology decisions extended beyond nominal turbine type and power rating. Technical discussions addressed turbine material, runner manufacture, shaft configuration, protection systems, hydraulic power unit, generator options, mechanical spares, installation drawings, general and sub-assembly drawings, schematic wiring diagrams, spare-part lists, and operation-and-maintenance manuals. The record explicitly states that documentation should be prepared after detailed design becomes available.

A contextual engineering note also noted concern that a welded runner configuration could influence vibration and efficiency compared with a monoblock configuration. Because this statement is contained in a working technical note rather than an experimental study, RELiS treats it as evidence that manufacturing configuration was considered relevant to operational performance—not as evidence of a causal performance difference. This distinction illustrates why the framework includes source provenance and evidence confidence.

Case A yields three design requirements for RELiS. First, technical readiness must include interface and documentation readiness rather than equipment specifications alone. Second, the selected technology should be assessed for spare-part and O&M information availability before acquisition. Third, evidence quality should be recorded so that a decision maker can distinguish verified design requirements, formal contractual requirements, expert judgment, and working assumptions.

Case C: manufacturing and supply-chain readiness

Case C provides stronger primary evidence for the manufacturing and supply-chain domain. The project risk register identifies non-conforming raw material, material delay, fabrication that does not conform to design drawings, assembly risk, and defects detected at final quality control. Preventive actions include detailed material specifications in the scope/contract, alternative suppliers, valid assembly drawings, incoming-material quality checks, and quality control throughout the production process. Recovery actions include returning non-conforming material and performing rework.

The associated inspection-test plan reinforces the same lifecycle logic. It specifies incoming-material inspection, fabrication and assembly controls, individual tests, customer acceptance, and rework or scrap when requirements are not met. Controls include approved drawings and wiring diagrams. These records show that manufacturability is not merely a factory issue: design clarity, supplier capability, material availability, inspection strategy, and rework exposure are all consequences of the technology choice.

For RELiS, the case supports readiness indicators for material availability, supplier dependence, alternative sourcing, drawing maturity, inspection feasibility, fabrication capability, spare-part strategy, lead time, and recovery options. These indicators should be evaluated before final technology commitment when remote logistics could amplify supply disruptions.

Case D: dynamic implementation conditions and decision change

Case D demonstrates that lifecycle conditions can invalidate assumptions during implementation. A formal meeting record documents a generator-related technical condition in which test voltage had increased but insulation resistance remained unacceptable, while the DC supply for battery charging experienced voltage drop. Mechanical and electrical work packages were dependent on generator readiness, and tuning required additional time. The parties proposed and agreed to an amendment based on the actual technical conditions.

The significance for RELiS is not the specific fault itself, but the decision pattern: implementation evidence altered scope, sequence, time dependency, and contractual action. Technology evaluation for remote systems should therefore examine recoverability, commissioning dependency, interface criticality, diagnostic readiness, and contingency options before acquisition. A lifecycle-informed decision model should also provide a structured path for feeding actual implementation conditions back into future technology evaluations.

Case B: maintainability, reliability, and lifecycle learning

Case B is the strongest downstream evidence set. A formal investigation of an operating small-hydropower unit covered the gearbox, regulating guide-vane pins and bushings, regulating shaft, guide-vane components, flywheel-generator coupling, flywheel bearing, turbine-shaft bushing, generator, hydraulic system, control system, battery rectifier, and transformer. The breadth of the investigation demonstrates that operational failure is a system-level phenomenon involving mechanical, electrical, hydraulic, instrumentation, documentation, and maintenance factors.

The investigation records show concrete maintainability and reliability issues. The gearbox was reported damaged. Regulating pins and bushings were worn and one bushing had become oval; the regulating shaft and guide-vane components were sufficiently worn that replacement or new manufacture was recommended. The flywheel-generator coupling was loose relative to the shaft and required coupling-set replacement. The flywheel bearing was damaged and reconditioning/rebabbiting was recommended, together with a recommendation to add pressurized and circulating lubrication. A turbine-shaft bushing also required replacement.

The generator and auxiliary systems added an information and condition-monitoring

dimension. The generator had a repaired/cracked mounting foot, while insulation and rotating-diode tests were acceptable. No temperature sensors were available on the two generator bearings, and a note indicated that existing generator temperature sensing was positioned at the air inlet rather than the winding. In the hydraulic system, the pressure-filling pump may not operate automatically, causing continuous pump operation and hot oil; pressure indication was unclear, the oil stock was insufficient, no filter was present on the pump discharge, and a hose to the guide-vane actuator was cracked.

The control-system investigation reported multiple unavailable or abnormal functions, including guide-vane position and limiter monitoring, water-level monitoring, temperature monitoring, the control unit, generator protection, frequency metering, guide-vane switching, AVR, and HPU oil-pressure control. The report explicitly notes the absence of a wiring diagram. This single finding is especially important to RELiS: missing technical documentation is not only a recordkeeping weakness; it can reduce maintainability, diagnostics, configuration understanding, and future modification confidence.

The case therefore provides a backward-looking evidence set for future decisions. Rather than treating failure investigation as an endpoint, RELiS treats it as a source of design knowledge. Questions such as sensor placement, lubrication architecture, component wear accessibility, control-system supportability, drawing completeness, local repair capability, and spare-part strategy become upstream criteria for the next technology selection. This creates the lifecycle-learning loop central to the proposed framework.

Lifecycle cost evidence: useful but not yet a full lifecycle-cost model

A related intervention cost record from the pseudonymized asset cluster provides limited but useful financial evidence. To protect commercial information, the manuscript reports only normalized cost shares: approximately 49.8% of the recorded intervention costs were materials, 41.8% services, and 8.4% overhead/supporting costs. The record also contains logistics, travel, site work, and component-related expenditure items.

This evidence is not a full lifecycle-cost (LCC) analysis because it does not include the complete sequence of acquisition, multi-year operation, planned maintenance, forced outage consequences, major overhaul, replacement, residual value, and disposal. It nevertheless shows why a remote-system technology decision should anticipate more than initial equipment price. RELiS therefore defines lifecycle-and-cost readiness as a domain, while leaving full LCC modeling to subsequent quantitative validation.

Table 3. Cross-case documentary synthesis.

Case	Lifecycle position	Documentary evidence pattern	RELiS domains informed
Case A	Acquire / engineering	Design, manufacturing configuration, drawings, manuals, spares	D2, D4, D5, D7
Case C	Manufacturing / QC	Material conformity, supplier delay, drawing validity, rework	D2, D4, D6, D7
Case D	Implementation/commissioning	Emergent field conditions, dependencies, schedules and amendments	D2, D3, D6, D7
Case B	Operate / maintain	Wear, couplings, bearings, hydraulics, controls, sensors, missing wiring diagram	D3, D5, D6, D7

The domain mapping in Table 3 should be interpreted together with the governance and feasibility baselines. D1 (System, Resource & Business-Value Fit) was informed primarily by the feasibility assessment, asset-management governance, and renewable-energy decision literature, whereas Cases A–D provided direct documentary support principally for D2–D7. Accordingly, the seven-domain RELiS architecture reflects an integrated synthesis of normative, feasibility, literature, and cross-lifecycle case evidence rather than derivation from the embedded cases alone.

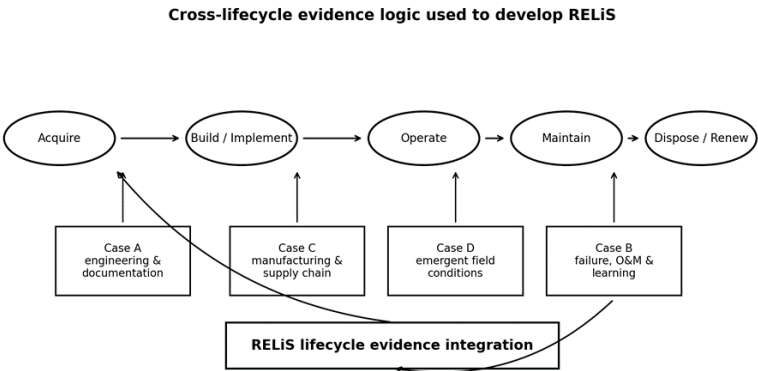


Figure 2. Cross-lifecycle evidence used to connect downstream learning with upstream decisions.

Development of the RELiS Framework
Design principles

Five design principles were derived from the literature and documentary evidence. First, RELiS is complementary: it does not replace feasibility studies, corporate asset-management policy, investment governance, O&M processes, or formal risk management. Second, it is lifecycle-informed: downstream evidence is eligible to influence upstream selection criteria. Third, it is evidence-traceable: every readiness judgment should identify its source, date, lifecycle stage, and confidence. Fourth, it is context-sensitive: remote logistics, local capability, system constraints, environmental exposure, and business value can change the relative importance of criteria. Fifth, it is extensible: the framework can later host expert weighting, MCDM ranking, lifecycle cost modeling, and sensitivity analysis without changing its evidence architecture.

Seven RELiS domains

Table 4. Proposed RELiS domains and indicative project-level criteria.

Code	Domain	Indicative criteria	Core decision question
D1	System, Resource & Business-Value Fit	Resource adequacy; demand/system compatibility; interconnection; strategic value; stakeholder requirements; local context	Does the option fit the energy resource, power system, organizational objectives, and service context?
D2	Technical & Engineering Readiness	Technology maturity; detailed design; interfaces; performance; commissioning; protection/control; documentation maturity	Can the option be designed, integrated, tested, and commissioned with sufficient technical confidence?
D3	Lifecycle & Cost Readiness	CAPEX; OPEX; maintenance; logistics; overhaul; replacement; proxy downtime; disposal/end-of-life	What cost commitments and lifecycle interventions are created beyond acquisition?
D4	Manufacturing & Supply-Chain Readiness	Material availability; supplier dependence; fabrication; QA/QC; alternative sourcing; spares; lead time; repairability	Can the option be manufactured, sourced, inspected, repaired, and supported under remote logistics?
D5	Maintainability & Reliability Readiness	Accessibility; inspection; condition monitoring; lubrication; sensors; tools; skills; reliability; failure recovery	Can the asset be monitored, maintained, repaired, and returned to service throughout its operating life?
D6	Risk, Safety & Resilience	Technical risk; project risks; logistics; environment; climate/geography; HSE; contingency; resilience	What can disrupt lifecycle value, and how detectable, preventable, and recoverable are those risks?
D7	Information, Knowledge & Lifecycle Learning	Data quality; drawings; wiring diagrams; manuals; configuration; provenance; lessons learned; feedback; change control	Is the decision supported by sufficient information, and can future evidence improve the next decision?

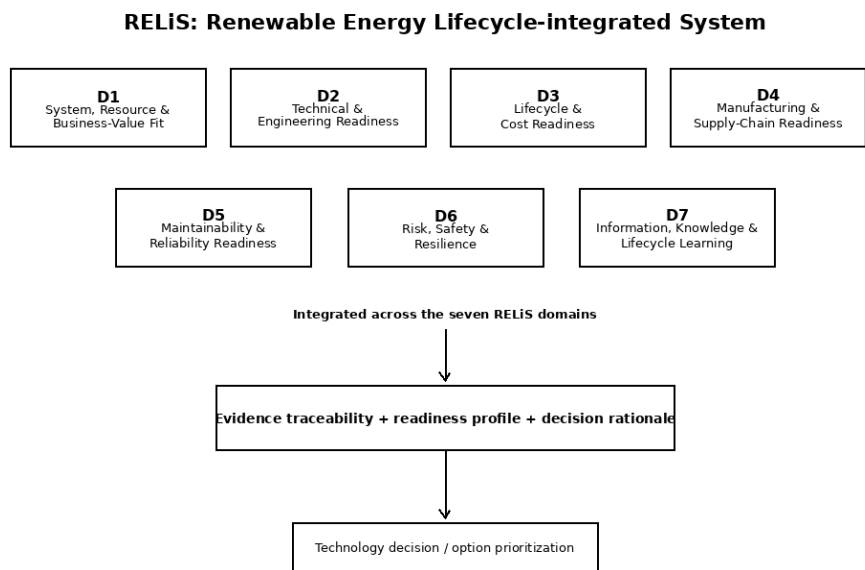


Figure 3. Proposed RELiS integrated lifecycle decision framework.
Relationship to existing governance

Table 5. RELiS as a complementary decision-support layer.

Mechanism	Primary role	Relationship with RELiS
Feasibility assessment	Determines whether a project/option is viable under defined technical, economic, environmental, and implementation requirements	Uses feasibility outputs as inputs; does not repeat the complete feasibility assessment
Corporate asset management	Defines value, lifecycle, risk, information, stakeholders, alignment, and improvement principles	Operationalizes those principles at renewable-energy technology-selection level
Generation O&M governance	Controls operation, maintenance, reliability, supply chain, lifecycle costs, safety, and feedback after/across acquisition	Feeds O&M requirements and downstream evidence into early evaluation
RELiS	Structures cross-stage readiness evidence and decision rationale	Creates a traceable project-level readiness profile to support option comparison

Proposed evidence-traceability logic

Each RELiS criterion should eventually be recorded with five metadata fields: evidence source, lifecycle stage, evidence type, confidence, and decision implication. A formal engineering drawing, for example, would receive a higher evidence status than an informal assumption; a confirmed failure investigation would be distinguished from an expert forecast. This design is intended to prevent numerical scoring from creating false precision when the underlying evidence quality is weak.

A future RELiS implementation can produce a readiness profile for each alternative technology. The current study does not prescribe final weights, readiness scales, evidence-confidence modifiers, normalization rules, or an aggregation equation. After content validation by experts, weights may be generated using AHP, Best-Worst Method, entropy, CRITIC, or hybrid subjective-objective methods, and alternatives may then be ranked using TOPSIS or another suitable MCDM method. The recent distributed-energy literature confirms that AHP and TOPSIS are common, but the choice of method should follow the decision problem rather than define it (Gallozzi et al., 2026). Any future scoring function should therefore be selected and validated empirically after the RELiS domains and indicators have been validated.

Discussion

What RELiS adds to renewable-energy MCDM

RELiS is not proposed as a new ranking algorithm. Its contribution lies upstream of the algorithm: defining an evidence architecture that incorporates lifecycle consequences

commonly dispersed across project stages. Conventional renewable-energy MCDM studies appropriately compare technical, economic, environmental, and social criteria, but the Case A–D evidence shows additional project-level readiness questions about drawing maturity, spare parts, manufacturability, supplier alternatives, rework, commissioning dependencies, instrumentation, lubrication, documentation, and failure learning. These issues can be decisive in remote systems even when a technology performs well on generic technical-economic indicators.

The distinction matters because a decision matrix can only be as useful as the evidence represented in its criteria. A technically sophisticated MCDM model can still underperform if maintainability, supply-chain vulnerability, or evidence of confidence are omitted. RELiS therefore prioritizes criterion completeness and evidence provenance before weighting. This is consistent with recent calls for context-sensitive renewable-energy decision frameworks and more careful criteria selection (Gallozzi et al., 2026).

What RELiS adds to asset-management governance

The corporate governance documents already contain many concepts that appear in RELiS: whole-lifecycle management, business value, risk, information quality, supply chain, lifecycle costs, reliability, and continuous improvement. RELiS does not claim these concepts are absent. Its proposed contribution is to make them operational in a specific decision moment—renewable-energy technology selection—by linking each readiness judgment to documentary evidence and to downstream lifecycle experience.

This relationship resembles strategic asset-planning research that combines system-level planning with structured decision analysis (Elsawah et al., 2019) and sustainability-oriented asset management that explicitly evaluates multiple consequences over time (Mohammadifardi et al., 2022). The case evidence adds a practical electricity-utility perspective: a worn bushing, missing wiring diagram, supplier delay, or commissioning dependency becomes useful not only for corrective action but also as a criterion-generating event for future technology selection.

Lifecycle learning as the distinctive feature

The most distinctive feature of RELiS is the explicit lifecycle-learning loop. Case B shows that operating assets produce detailed knowledge about wear mechanisms, sensing gaps, lubrication, supportability, control-system health, and documentation quality. OM-01 already requires feedback for improvement and subsequent planning. RELiS provides a proposed project-level destination for that feedback: a structured technology-evaluation domain and indicator set. The decision framework can therefore evolve as organizational experience accumulates.

This feature also prevents a false separation between 'project' and 'asset.' The assets created by a project will later generate maintenance demand, outages, spares consumption, engineering changes, and renewal decisions. Conversely, those downstream experiences should inform the design and procurement of the next project. In remote power systems, where recovery options are constrained, closing this loop is especially important.

Implications for remote power systems

Remote systems increase the consequence of decision errors because logistics, redundancy, specialist access, and supplier response can be constrained. RELiS therefore shifts the technology-selection question from 'Which option is best at the decision date?' toward 'Which option has the strongest evidence-supported readiness to create value across its lifecycle in this specific system?' This wording encourages decision makers to examine not only expected output but also supportability, recoverability, and information continuity.

The framework is particularly compatible with small hydropower, hybrid microgrids, solar-plus-storage, and other decentralized renewable systems. However, the criteria should not be assumed to carry identical weights across technologies. Hydropower may emphasize

rotating equipment, hydraulic systems, mechanical spares, and site access; solar-plus-storage may emphasize battery degradation, power-electronic replacement, firmware/support, thermal management, and recycling. RELiS is intended to preserve a stable lifecycle architecture while allowing technology-specific indicators to vary.

Managerial and Policy Implications

For asset-intensive utilities, RELiS can be used as a pre-approval checklist and evidence matrix before technology commitment. It can require engineering teams to identify missing data, operations teams to specify maintainability and monitoring needs, supply-chain teams to assess supplier and spare-part risks, project teams to identify commissioning and interface dependencies, and asset managers to define lifecycle costs and risk expectations. The resulting readiness profile could be attached to a feasibility or design-review package rather than operating as a separate governance bureaucracy.

A second implication concerns organizational learning. Failure investigations and major maintenance reports often contain valuable design knowledge, but that knowledge can remain within maintenance or engineering records. RELiS provides a route for converting recurring findings into formal criteria, thresholds, or evidence requirements for new projects. Over time, a digital RELiS implementation could connect asset-information systems, failure databases, engineering-change records, cost data, and project lessons learned to create a reusable decision knowledge base.

For policymakers and public utilities pursuing renewable expansion in remote regions, the framework suggests that local-content or initial-cost objectives should be evaluated together with lifecycle serviceability. Local manufacturing can create strategic value, but readiness should consider material quality, inspection capability, repairability, supplier resilience, documentation ownership, and skill availability. Likewise, imported technology may offer high initial performance but create long-term dependency if critical spares, software, or technical knowledge are inaccessible. RELiS makes these trade-offs explicit rather than treating them as post-procurement issues.

Limitations and Future Validation

The first limitation is organizational and technological scope. The framework was developed from a pseudonymized internal evidence corpus within one state-owned electricity utility and is demonstrated primarily through small-hydropower cases. Cases were purposively selected to provide analytic coverage across lifecycle stages rather than statistical representativeness; therefore, the findings should not be interpreted as population estimates or as representative of all projects within the study organization. Although the lifecycle logic may be transferable, the indicator set should be validated before application to other technologies, organizations, or remote-system contexts.

Second, the study is documentary. It does not yet include interviews or structured expert validation. A next-stage study should recruit approximately 8–12 experts across planning, engineering, manufacturing, supply chain, operations, maintenance, project management, risk/HSE, and renewable-energy assessment. Each RELiS indicator can be assessed for relevance, clarity, importance, and applicability, followed by content-validity analysis and qualitative revision.

Third, the study does not estimate criterion weights or rank technology alternatives. After content validation, a hybrid weighting method could combine expert preference with objective project data. Sensitivity analysis should be used to test whether rankings remain stable under alternative weights, because renewable-energy MCDM outcomes can be highly dependent on criteria selection and weighting assumptions.

Fourth, the available cost evidence is intervention-specific rather than a complete LCC dataset. Future validation should assemble acquisition costs, operating expenditure, preventive and corrective maintenance, overhaul, logistics, spare parts, downtime/lost-

generation proxies, replacement cycles, life extension, and disposal. This would allow D3 to move from readiness assessment to a full economic lifecycle model.

Finally, pseudonymization protects source-level confidentiality but reduces reproducibility of source details. To mitigate this limitation, the study uses coded document sets, a source hierarchy, explicit evidence descriptions, and a chain-of-evidence logic. A future publication may provide a pseudonymized codebook and evidence matrix where authorization by the data-owning organization permits.

CONCLUSION

This study develops RELiS, a Renewable Energy Lifecycle-integrated System framework for project-level technology decisions in remote power systems. The central finding is not that lifecycle governance is absent. On the contrary, the governance baseline in the study organization already adopts whole-lifecycle management, risk-informed decisions, lifecycle costs, supply chain, asset information, reliability, and continuous improvement. The unresolved practical problem is how to translate evidence distributed across lifecycle stages into a consistent technology-evaluation structure.

Documentary evidence from four pseudonymized small-hydropower cases demonstrates this need. Upstream engineering records show the importance of design maturity, documentation, spares, and manufacturing configuration; manufacturing records show material, supplier, quality, and rework risks; implementation records show how field conditions can change scope and timing; and downstream investigation records show how wear, lubrication, instrumentation, control systems, documentation, and repairability generate lessons for future designs. Together with the governance, feasibility, and literature baselines, RELiS organizes these observations into seven domains covering system/business fit, engineering, lifecycle cost, manufacturing/supply chain, maintainability/reliability, risk/resilience, and information/lifecycle learning.

The proposed framework is therefore best understood as a complementary decision-support artifact within an existing asset-management ecosystem. Its next research stage is empirical validation: expert review of domains and indicators, quantitative weighting, technology-option demonstration, lifecycle-cost modeling, and sensitivity analysis. Until those stages are completed, RELiS should be presented as a systematically developed and documentarily demonstrated framework rather than a proven performance-improvement method.

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