

Open Radio Access Network (Open RAN) Deployment Strategies for Rural and Remote Areas: A Systematic Literature Review

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Open Radio Access Network (Open RAN) Deployment Strategies for Rural and Remote Areas: A Systematic Literature Review

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ABSTRACT

Extending mobile connectivity to sparsely populated rural and remote regions remains a persistent global challenge, shaped by low population density, constrained terrestrial backhaul, unreliable power supply, and low average revenue per user (ARPU). Open Radio Access Network (Open RAN), characterized by disaggregated O-RU, O-DU, and O-CU functions, open interfaces, Service Management and Orchestration (SMO), and Radio Intelligent Controller (RIC)-enabled automation, offers a promising architectural pathway for addressing these constraints through vendor diversity, infrastructure sharing, programmable optimization, and cost-transparent deployment models. This systematic literature review follows PRISMA guidance and synthesizes 27 peer-reviewed studies, standards documents, industry white papers, and field deployment reports published between January 2018 and March 2026. The review critically evaluates six mutually reinforcing deployment strategy dimensions: topology-aware functional split selection; hybrid backhaul architectures integrating fiber, microwave, satellite, and TV White Space (TVWS); infrastructure and spectrum sharing models, including neutral-host MOCN/MORAN and OneRAN pooling; SMO/RIC-driven energy and mobility automation; renewable energy integration for off-grid autonomy; and total cost of ownership (TCO)-based viability modeling. Reported quantitative evidence includes approximately 20% dynamic power reduction through ORTP-based xApps, a 10% OPEX reduction over five years through SMO automation, and throughput gains through infrastructure pooling; however, these claims remain unevenly validated across simulations, vendor studies, pilot reports, and peer-reviewed field measurements. The review identifies eight major research gaps, including the absence of standardized rural Open RAN TCO frameworks, limited long-term multi-vendor field evidence, unresolved security and SLA enforcement for neutral-host deployments, and weak linkage between technical design choices and socioeconomic outcomes. The paper provides actionable guidance for operators, regulators, vendors, tower companies, and development agencies seeking to deploy Open RAN in rural and remote contexts.

Keywords: Open RAN; O-RAN; rural connectivity; functional split; hybrid backhaul; satellite backhaul; TV White Space; SMO; RIC; neutral host; renewable energy; NTN; OneRAN; energy efficiency; systematic literature review

1. INTRODUCTION

Mobile connectivity remains profoundly unequal across the globe. According to the International Telecommunication Union (ITU), approximately 2.6 billion people remain unconnected, with the majority residing in rural and remote regions of sub-Saharan Africa, South and Southeast Asia, and Latin America. The structural barriers to rural mobile deployment are well-documented: low and dispersed population density reduces the viability of per-site business cases; terrestrial fiber infrastructure is absent or cost-prohibitive; power grid availability is limited, with many remote sites requiring diesel generators that account for 35–40% of operational expenditure (OPEX); and low ARPU dampens mobile network operator (MNO) incentive to invest [1, 2, 3].

Traditional radio access network (RAN) architectures — dominated by proprietary, integrated base stations from a small number of equipment vendors — compound these structural barriers. High capital expenditure (CAPEX) per site, limited vendor competition, and the absence of flexible sharing mechanisms have historically made rural RAN economics unviable without substantial public subsidy or universal service fund support [4, 5].

Open RAN (Open Radio Access Network), standardized primarily by the O-RAN Alliance and underpinned by 3GPP NR functional split specifications, disaggregates the traditional base station into interoperable O-RU, O-DU, and O-CU components communicating over open interfaces (F1, E1, E2, O1, A1, and the eCPRI/fronthaul interface). This architectural openness introduces SMO and RIC layers that enable AI/ML-driven lifecycle management, intent-based policy enforcement, and multi-timescale optimization. The resulting programmability, vendor diversity, and sharing potential theoretically address several rural deployment barriers simultaneously [1, 6, 7].

However, Open RAN deployment in rural and remote contexts presents unique technical and operational challenges that are not encountered in urban or suburban deployments. Constrained fronthaul and midhaul transport limits the feasibility of lower-layer functional splits (e.g., Option 7.2x) that dominate urban deployments. Multi-hop satellite or TVWS backhaul introduces latency and jitter inconsistent with tight time-domain control loops. The absence of on-site technical expertise demands higher automation through zero-touch provisioning. Multi-vendor integration complexity — already a challenge in controlled test environments — is exacerbated by harsh environmental conditions, limited spares logistics, and remote site management [1, 8, 9].

This paper presents a systematic literature review of Open RAN deployment strategies tailored to rural and remote areas. The review follows the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework and synthesizes evidence from peer-reviewed academic literature, O-RAN Alliance technical specifications, GSMA Intelligence reports, and operator/vendor deployment case studies published between January 2018 and March 2026. The primary objectives are to: (i) characterize current Open RAN deployment strategies for rural contexts; (ii) evaluate quantitative evidence supporting each strategy; (iii) map interdependencies among architectural, backhaul, energy, and sharing dimensions; and (iv) identify open research gaps requiring further investigation.

The remainder of this paper is organized as follows. Section 2 describes the review methodology. Section 3 presents the Open RAN reference architecture and rural adaptation requirements. Section 4 synthesizes deployment strategies across six thematic dimensions. Section 5 evaluates deployment challenges and barriers. Section 6 provides a comparative analysis of deployment strategies and KPIs. Section 7 presents an integrated optimization framework. Section 8 provides stakeholder recommendations. Section 9 derives policy implications from the subsidy trigger condition, including implications for African rural connectivity. Section 10 identifies research gaps and future directions. Section 11 discusses limitations of the review and the current evidence base. Section 12 concludes the paper.

2. REVIEW METHODOLOGY

2.1 Search Strategy and Eligibility Criteria

This systematic literature review was conducted following the PRISMA 2020 framework. The initial database search was conducted between 1 and 15 March 2026, and the search was updated on 31 March 2026 to capture recent publications and technical reports within the review window. Electronic databases searched included IEEE Xplore, Scopus, Web of Science, ACM Digital Library, and Google Scholar. Grey literature sources included the O-RAN Alliance document repository, GSMA Intelligence research reports, 3GPP technical specifications, ITU-D reports, and selected vendor/operator white papers from Ericsson, Nokia, Mavenir, Rakuten, and DISH Network. The search strings were adapted to the syntax of each database while preserving the same conceptual terms.

The following core Boolean search string was applied across databases: ("Open RAN" OR "O-RAN" OR "vRAN" OR "virtual RAN") AND ("rural" OR "remote" OR "underserved" OR "low-density" OR "unconnected"). Eligibility criteria required: (i) publication in English between January 2018 and March 2026; (ii) relevance to rural, remote, underserved, or low-density deployment contexts; and (iii) engagement with at least one of the following dimensions: architecture, backhaul, energy, sharing models, policy, or business case. At title-and-abstract screening, a record was retained if it explicitly addressed Open RAN/vRAN architecture or an enabling rural-connectivity component. At full-text screening, a study was included only if it provided empirical evidence, simulation/analytical modelling, standards-based architecture, or a technically substantive deployment case. Studies were excluded if they addressed only urban/suburban Open RAN, lacked methodological transparency, contained only descriptive marketing claims, or did not provide enough technical detail to support synthesis.

Table 1. PRISMA Flow — Study Selection Summary

Stage	Item	Count / Outcome
Identification	Records identified via IEEE Xplore, Scopus, Web of Science, ACM DL, Google Scholar	n = 312
Identification	Additional records from grey literature (GSMA, O-RAN Alliance, 3GPP, ITU, vendor WPs)	n = 48
Screening	Duplicates removed	n = 61
Screening	Records screened by title and abstract	n = 299
Screening	Records excluded (out-of-scope, non-English, pre-2018)	n = 214
Eligibility	Full-text articles assessed for eligibility	n = 85
Eligibility	Full-text excluded (insufficient empirical/analytical content)	n = 58
Included	Studies included in qualitative synthesis	n = 27
Included	Studies included in quantitative analysis (KPI data)	n = 14

Source: Authors' compilation following PRISMA 2020 guidelines. n = number of records at each stage.

2.2 Data Extraction and Synthesis

Title-and-abstract screening and full-text eligibility assessment were performed independently by both authors using the pre-defined inclusion and exclusion rules described above. Disagreements were resolved through discussion and reference to the primary source. Data extraction was then performed using a pre-defined extraction template capturing: source category (peer-reviewed, standards/specification, industry white paper, operator/vendor report, or pilot case); study type (empirical, simulation, analytical, review); deployment scenario (greenfield, brownfield, neutral host, pilot); geographic context; O-RAN components addressed (O-RU, O-DU, O-CU, SMO, Near-RT RIC, Non-RT RIC); backhaul technology; energy solution; quantitative KPIs reported (CAPEX, OPEX, throughput, energy saving, availability); and identified limitations. This separation of evidence categories was used during synthesis to avoid treating peer-reviewed evidence and grey-literature claims as equivalent.

3. OPEN RAN REFERENCE ARCHITECTURE AND RURAL ADAPTATION

3.1 O-RAN Alliance Reference Architecture

The O-RAN Alliance has defined a reference architecture that decomposes the traditional monolithic base station (eNB/gNB) into three principal radio network functions: the O-RU (radio-frequency processing, limited PHY), the O-DU (upper PHY, MAC, RLC), and the O-CU (split into O-CU-CP for PDCP/RRC control plane and O-CU-UP for PDCP/SDAP user plane). These components communicate over standardized open interfaces: F1 between O-DU and O-CU; E1 between O-CU-CP and O-CU-UP; the Fronthaul interface (based on eCPRI with 3GPP Option 7.2x) between O-RU and O-DU. The SMO manages all O-RAN functions via the O1 interface, while the Non-RT RIC communicates policy and ML model guidance to the Near-RT RIC via the A1 interface. The Near-RT RIC interacts with O-DU and O-CU via the E2 interface, enabling sub-second control loop execution through xApps [1, 6, 7].

Figure 1 illustrates the complete O-RAN reference architecture as adapted for a rural and remote deployment scenario, highlighting the placement of SMO/Non-RT RIC at a centralized or regional level, Near-RT RIC at a regional edge node, and O-DU co-located with or proximate to the O-RU at the remote site.

Figure 1. O-RAN Reference Architecture — Component Hierarchy and Interface Map (Rural Adaptation)

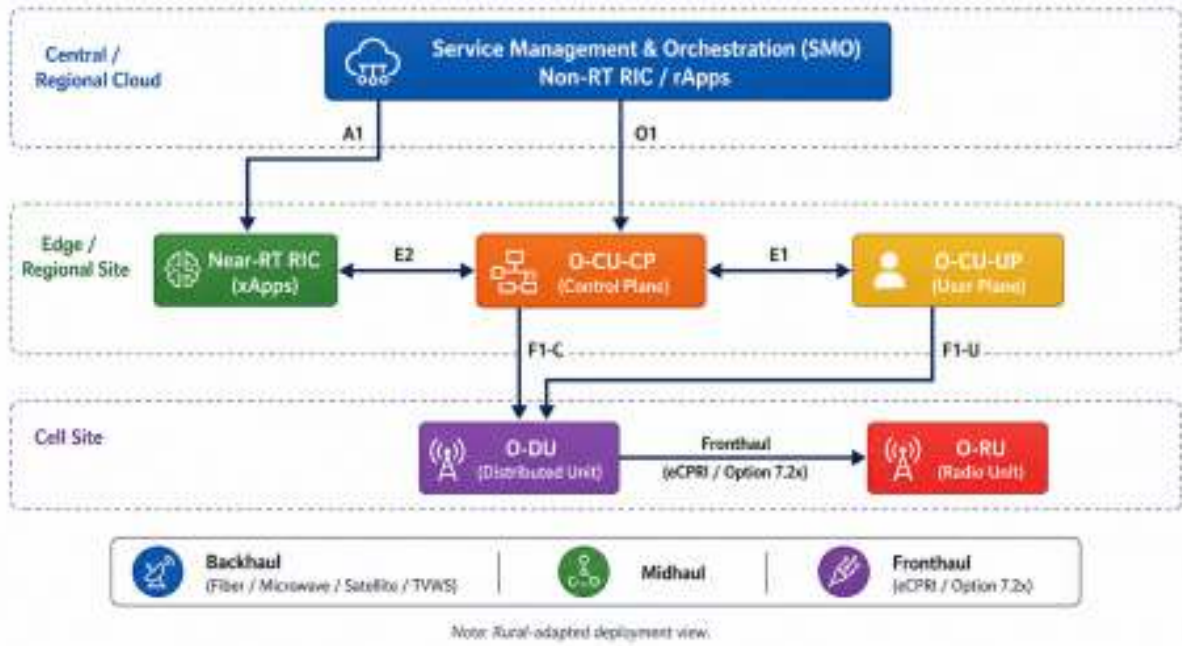


Figure 1. Rural-adapted O-RAN reference architecture.

Note: Arrows indicate standardized O-RAN Alliance interfaces. SMO/Non-RT RIC may be centralized or regionally shared across multiple clusters. Near-RT RIC is placed at the regional edge to minimize E2 latency. O-DU/O-RU co-location is preferred where fronthaul constraints are severe.

3.2 Functional Split Options and Rural Feasibility

The choice of functional split between O-DU and O-RU is among the most consequential architectural decisions for rural Open RAN deployment. The fronthaul bandwidth and latency values commonly associated with lower-layer splits should be interpreted as deployment-planning bounds rather than fixed universal constants. In particular, Option 7.2x transport demand depends strongly on channel bandwidth, antenna order, sectorization, numerology/subcarrier spacing, compression method, quantization, synchronization accuracy, and vendor implementation. Even with compression and optimized transport, lower-layer splits impose much stricter latency and bandwidth requirements than higher-layer splits, making them difficult to support over satellite, TVWS, or multi-hop microwave backhaul. Higher-layer splits (Options 1 and 2) tolerate significantly higher latency and lower bandwidth, enabling their use over commercially viable rural transport technologies [1, 10].

The O-RAN Alliance has introduced the concept of dynamic split adaptation driven by SMO policies, enabling the functional split to be adjusted in response to real-time backhaul conditions. This is particularly valuable in hybrid backhaul scenarios where primary transport (fiber/microwave) may fail over to satellite links with different latency/bandwidth profiles [1, 11].

Table 2. O-RAN Functional Split Options — Rural Feasibility Analysis

Split	O-RAN Name	BW Bound	Latency Bound	Rural Feasibility	Backhaul
Option 1	PDCP-RLC split	< 1 Gbps	10-50 ms class	High - suited to satellite/TVWS	LEO/GEO, TVWS, microwave
Option 2	RLC-MAC split (F1)	1-10 Gbps	<=10 ms class	Moderate - aggregation fiber/microwave	Fiber, short-hop microwave
Option 6	MAC-PHY lower	10-100 Gbps	<=1 ms class	Low - needs dedicated fiber/low-latency μ wave	Dark fiber only
Option 7.2x	Lower PHY/IQ split	100-200+ Gbps/sector; config.-dependent	$\approx$ 100 μ s class; impl.-dependent	Very low over satellite/long hops	Co-located O-DU/O-RU
Dynamic split (SMO-driven)	Adaptive (SMO policy)	Variable	Variable	High - constrained backhaul	Hybrid with SMO orchestration

Sources: [1, 6, 10, 12]. BW = bandwidth; LoS = line-of-sight; SMO = Service Management and Orchestration. Values are indicative deployment-planning bounds, not fixed universal requirements; actual fronthaul demand varies with bandwidth, antenna order, sectorization, numerology, compression, synchronization, and implementation profile.

Equation (1) formalizes the fronthaul latency constraint that governs functional split selection:

$$L_{fh(split)} \leq L_{\max(split)} \quad (1)$$

where $L_{fh(split)}$ is the achievable fronthaul latency for a selected split, and $L_{\max(split)}$ is the maximum tolerable latency used for deployment planning. Typical planning bounds are $L_{\max(7.2x)}$ in the approximately 100 μs class, $L_{\max(2)}$ around the 10 ms class, and $L_{\max(1)}$ around the 50 ms class. These values are not universal limits; they vary with radio configuration, implementation profile, synchronization design, traffic engineering, and the extent of fronthaul compression.

For rural sites connected via LEO satellite with round-trip latencies commonly in the tens of milliseconds, Option 1 is generally the practical split choice, while Option 2 may be feasible only where local PHY/HARQ handling and sufficiently stable low-latency transport are available. Lower-layer options such as Option 7.2x usually require O-DU/O-RU co-location or dedicated low-latency terrestrial transport rather than long-haul satellite or deep multi-hop rural backhaul [12].

3.3 Spectrum Considerations for Rural Open RAN

Spectrum availability and pricing are primary determinants of rural coverage economics. Low-band spectrum (sub-1 GHz, particularly 700 MHz and 850/900 MHz bands) offers the propagation characteristics — coverage radii of 5–15 km per site and superior building penetration — essential for cost-effective rural deployment. GSMA analysis demonstrates that low-band spectrum availability is the most significant single policy lever for improving rural coverage economics, enabling reduction in site counts and associated CAPEX/OPEX [13].

Table 3. Spectrum Options for Rural Open RAN — Coverage, Suitability, and Integration Characteristics

Band / Technology	Frequency Range	Coverage Radius	Rural Suitability	Open RAN Integration	Key References
Sub-1 GHz (700/850/900 MHz)	700–960 MHz	5–15 km	Excellent – deep rural; low path loss; building penetration	O-RU multi-band; SMO-controlled power scaling	[1, 3, 13]
1800/2100 MHz (LTE refarm)	1.8–2.1 GHz	2–5 km	Good – capacity layer where available	Standard O-RAN 7.2x; DSS capable	[1, 14]
2.6/3.5 GHz (5G NR)	2.5–3.7 GHz	0.5–2 km	Limited – coverage holes in sparse rural; best for aggregation nodes	mmWave O-RU; high-layer split required	[1, 15]
TVWS (UHF whitespace)	470–790 MHz (region-dependent)	10–50 km	Very High – licence-exempt; excellent propagation	O-RAN backhaul or access; SMO interference management	[8]
LEO/MEO Satellite (NTN)	Ka/Ku/L-band	Continental	Excellent for backhaul; emerging for access (NTN NR)	O-RAN NTN functional split; handover xApp required	[12]
Licensed Microwave	6–42 GHz	5–50 km (LoS)	Good – point-to-point backhaul or midhaul for aggregation	Transport-aware SMO; fronthaul latency budgeting	[1, 10, 12]

Sources: [1, 3, 8, 10, 12, 13, 15]. Coverage radii are indicative for flat terrain; actual coverage depends on propagation environment, antenna height, and link budget.

4. DEPLOYMENT STRATEGY SYNTHESIS

Based on the systematic review, six primary deployment strategy dimensions emerge from the literature. These dimensions are not mutually exclusive; optimal rural Open RAN deployments typically combine elements from multiple dimensions in a topology-aware configuration.

4.1 Topology-Aware Architecture and SMO/RIC Placement

A consistent finding across academic and industry literature is that Open RAN functions must be placed with explicit awareness of rural topology constraints. Martian et al. [1] and Bonati et al. [11] recommend that O-DU and O-CU be placed at regional edge cloud nodes (small regional data centers or edge co-location facilities) rather

than at central cloud data centers, in order to balance fronthaul latency requirements with midhaul capacity constraints. The SMO/Non-RT RIC is placed centrally or shared regionally for ML model training and policy management, while the Near-RT RIC is deployed at the regional edge to enable sub-second E2 control loops without incurring central data center round-trip latency [1, 11].

The SMO and RIC layers represent critical operational intelligence for rural deployments. SMO-enabled intent-driven lifecycle management allows unattended sites to be managed remotely, reducing the requirement for on-site technical staff — a significant OPEX component for remote rural deployments. Niklasson et al. [16] estimated that SMO-driven automation can reduce RAN OPEX by approximately 10% over a five-year brownfield deployment horizon.

Ndikumana et al. [17] propose an optimization framework for SMO-guided resource allocation in renewable-powered rural fixed wireless access (FWA) scenarios, formulating the joint problem of power allocation, functional split selection, and user scheduling as a mixed-integer non-linear program (MINLP). The authors demonstrate that SMO-level coordination across O-DU/O-CU placement and renewable energy harvesting can simultaneously improve energy autonomy and user throughput, establishing a formal quantitative basis for integrated topology-energy optimization.

Figure 2 illustrates the RIC-based automation loop architecture for rural Open RAN energy and mobility management, depicting the hierarchical interaction between Non-RT RIC rApps, Near-RT RIC xApps, and O-DU/O-RU control points.

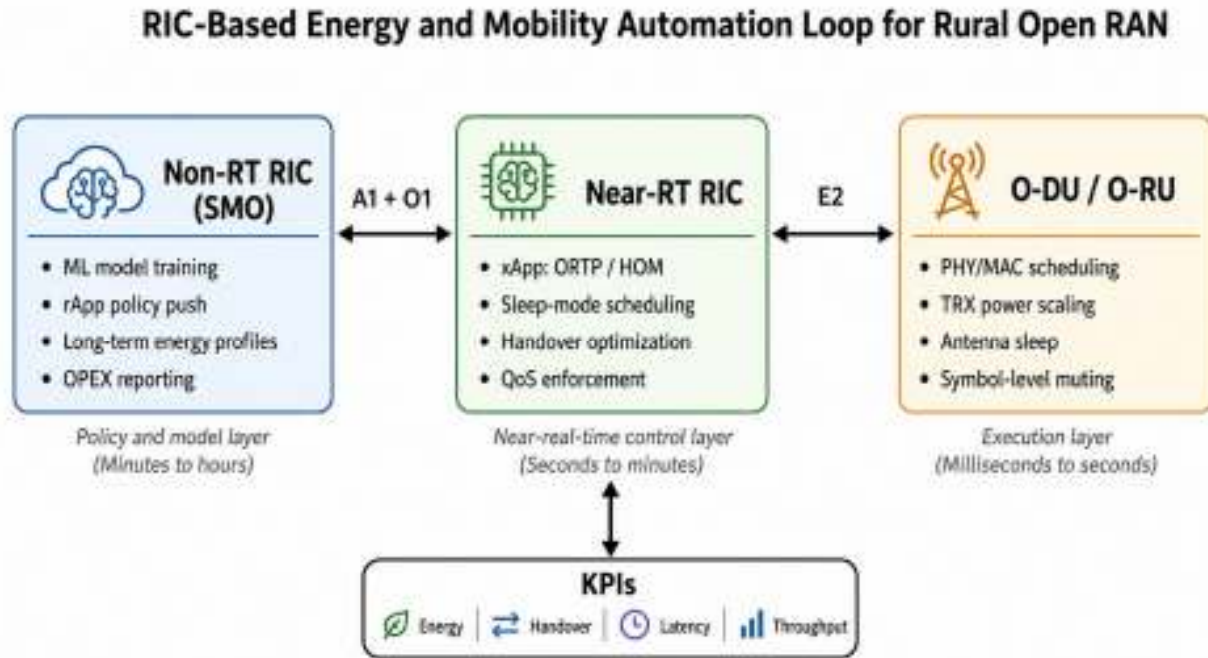


Figure 2. RIC-enabled energy and mobility control loop for rural Open RAN.

The Non-RT RIC trains ML models and pushes A1 policies on timescales of seconds to minutes. The Near-RT RIC executes xApps (e.g., ORTP, handover optimization) on sub-second timescales via E2 interface. O-DU/O-RU apply PHY-level energy levers (TRX sleep, symbol muting, power scaling).

4.2 Hybrid Backhaul Architecture

Rural backhaul is characterized by a heterogeneous mix of technologies with distinct cost, latency, and availability profiles. No single backhaul technology satisfies all rural deployment scenarios; practical deployments therefore require hybrid architectures that combine technologies in a hierarchical topology [8, 12].

The emerging consensus in the literature is a three-tier hybrid backhaul model: (i) fiber or licensed microwave for high-capacity aggregation node connections where available; (ii) LEO/MEO/GEO satellite for last-mile connectivity, backup, or deep rural sites where terrestrial infrastructure is economically unviable; and (iii) TVWS for backhaul or access in spectrum-rich environments where regulatory frameworks permit unlicensed use in the UHF band [8, 12].

Figure 3 presents the hybrid backhaul reference architecture recommended for rural Open RAN deployments, illustrating the layered topology from core network to end user with associated transport technology choices.

Figure 3. Hybrid Backhaul Architecture for Rural Open RAN – Layered Transport Topology

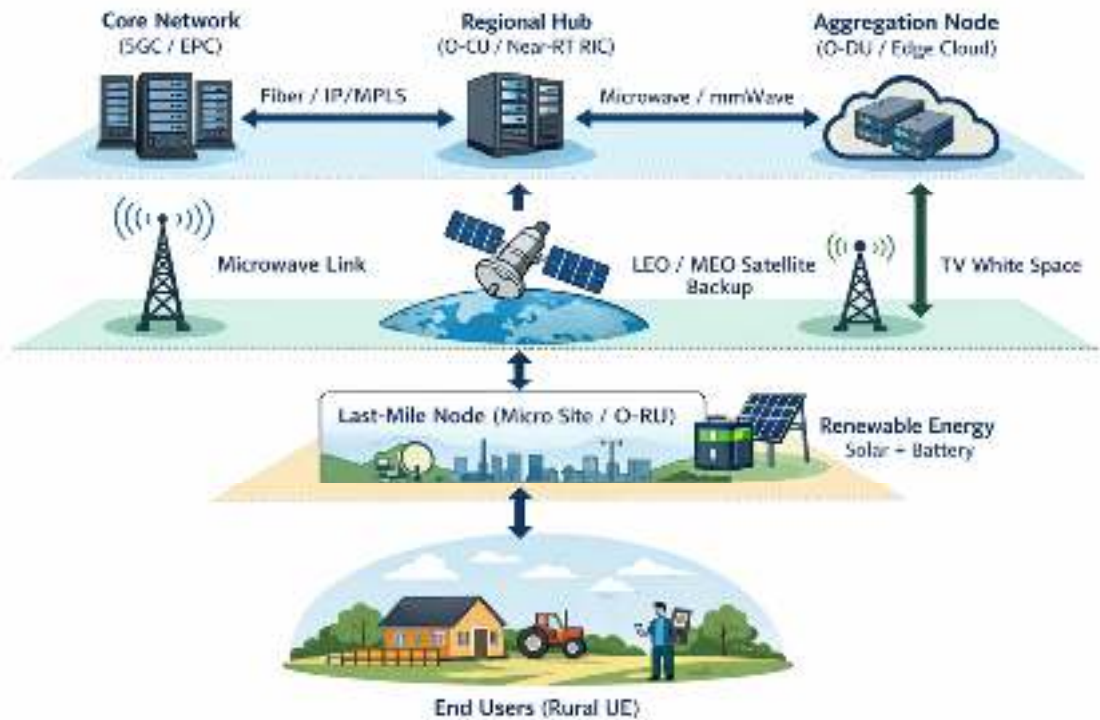


Figure 3. Hybrid backhaul architecture for rural Open RAN.

Backhaul technology selection is governed by SMO transport-aware policies. LEO satellite is recommended for last-mile and backup; TVWS for deep rural access where regulatory frameworks exist; microwave for aggregation hops.

Seeram et al. [12] provide the most comprehensive analytical treatment of LEO satellite integration with O-RAN functional splits. Their work identifies a fundamental trade-off: regenerative LEO payloads (which process O-RAN protocols onboard the satellite) reduce handover delay and enable lower-layer splits, but impose significant onboard processing constraints. Non-regenerative (bent-pipe) architectures are simpler but constrain functional splits to Options 1–2 due to the propagation delay budget. The authors model this as a latency-throughput Pareto optimization problem, establishing that handover delay increases approximately linearly with the number of LEO handover events per unit time, while onboard processing capacity determines the feasible functional split option set.

Parson et al. [8] document the GSMA/NuRAN pilot deployment in Northern Ghana, which implemented TVWS backhaul at seven rural sites. The pilot combined low-power O-RAN-compatible base stations (NuRAN LiteCell), TVWS backhaul, and solar power in a neutral-host commercial model. The case is valuable because it supports field feasibility of a TVWS-enabled, low-power rural connectivity stack under real operating conditions. However, it should not be interpreted as proof of long-term commercial sustainability, because independently audited OPEX, site availability, traffic growth, revenue, churn, maintenance cost, and multi-year performance data are not publicly disclosed.

4.3 Infrastructure and Spectrum Sharing Models

Infrastructure sharing - both passive (towers, power, shelter) and active (RAN equipment and spectrum) - is a critical cost-reduction lever for rural Open RAN. The literature documents a spectrum of sharing models, from passive sharing to full infrastructure pooling (OneRAN), each with distinct technical complexity, regulatory requirements, and cost-sharing profiles [18, 19, 20].

Neutral-host models, in which a single infrastructure provider hosts RAN equipment serving multiple MNO tenants, are particularly well-suited to rural contexts where per-operator site economics are unviable. The O-RAN

architecture enables neutral-host deployments through its multi-tenant orchestration capabilities in the SMO, which can manage independent PLMN slices on shared hardware. Two principal technical models are documented: MOCN (Multi-Operator Core Network), in which multiple operators share the same radio access network and spectrum, requiring sophisticated cross-PLMN orchestration; and MORAN (Multi-Operator Radio Access Network), in which operators share physical infrastructure but maintain independent spectrum allocations, with simpler operational coordination [20].

Sheikh et al. [19] present the most analytically rigorous treatment of full infrastructure pooling through the OneRAN concept. Analyzing a 52 km highway LTE corridor in Finland with measurements from three commercial MNOs, the authors demonstrate that full RAN resource pooling yields throughput gains that scale multiplicatively with the number of operators pooled, following the trunking efficiency relationship expressed in Equation (2):

$$T_{pool} = \eta_{trunking} \sum_{i=1}^N C_i, \quad \eta_{trunking} > 1 \quad (2)$$

where T_{pool} is pooled aggregate throughput, $\eta_{trunking}$ is the trunking-efficiency factor or OneRAN multiplicative gain, C_i is the capacity contribution of the i -th resource, and N is the number of pooled resources. Values of $\eta_{trunking}$ greater than one represent statistical multiplexing gains from pooling independent operator traffic flows.

Alam et al. [7] provide a comprehensive survey of network slicing in O-RAN, demonstrating that slicing-aware orchestration spans RAN, transport network (TN), and core network (CN) domains simultaneously. The authors emphasize that meaningful end-to-end slicing for rural neutral-host deployments requires aligned contributions across O-RAN Alliance, 3GPP, ETSI NFV, and IETF standards bodies — a coordination challenge with no current comprehensive solution.

4.4 Open RAN Sharing Advantage

A defining structural advantage of Open RAN over proprietary RAN architectures — particularly relevant for rural deployment economics — is its inherent compatibility with multi-operator infrastructure sharing. The open interface and multi-tenant orchestration design of the O-RAN Alliance architecture enables sharing arrangements that are technically complex or commercially infeasible with vendor-locked proprietary equipment. Two mathematical relationships capture the cost dynamics of this sharing advantage.

4.4.1 Cost Proportionality with Number of Sharing Operators

The first relationship, derived from the sharing cost model in Equation (3), establishes that per-operator cost scales inversely with the number of participating operators while also accounting for coordination overhead:

$$C_{share} = \left(\frac{C_{singleMNO}}{N_{MNO}} \right) \times (1 + \delta_{coord}), \quad \delta_{coord} \in [0.05, 0.20] \quad (3)$$

where C_{share} is shared cost per operator, $C_{singleMNO}$ is standalone cost for one MNO, N_{MNO} is the number of participating MNOs, and δ_{coord} is the coordination overhead factor associated with governance, SLA management, and inter-operator settlement.

The proportionality term $\frac{1}{N_{MNO}}$ captures the first-order cost division: a single tower, power system, backhaul link, and RAN equipment portfolio serving N operators incurs approximately $\frac{1}{N}$ of the cost per operator relative to independent deployment. This relationship is directly observed in Sheikh et al. [19], whose analytical model of the OneRAN concept for a 52 km Finnish highway corridor shows that full resource pooling across three MNOs reduces per-operator infrastructure cost in proportion to the sharing degree, while simultaneously delivering multiplicative throughput gains through statistical multiplexing.

The coordination overhead factor δ_{coord} — estimated at 5–20% based on observed neutral-host and MORAN deployments [19, 20] — represents the efficiency loss attributable to inter-operator coordination: governance structures, inter-PLMN orchestration complexity, SLA management, and the transactional costs of cross-operator settlement. The wide range of δ reflects the maturity of the sharing arrangement: voluntary infrastructure sharing between two operators with aligned incentives may achieve $\delta \approx 0.05$, while mandated spectrum pooling across operators with competing commercial interests may incur δ approaching 0.20.

Open RAN reduces δ through architectural means. The SMO's multi-tenant orchestration capability — specifically its ability to manage independent PLMN slices on shared O-Cloud infrastructure — automates much of the per-tenant resource allocation and performance monitoring that would otherwise require manual inter-operator coordination. Network slicing, as surveyed by Alam et al. [7], provides the technical mechanism through

which per-operator service guarantees (throughput, latency, isolation) can be enforced algorithmically rather than through bilateral SLA negotiation, reducing governance overhead and in principle lowering δ toward the minimum achievable bound.

4.4.2 Throughput Multiplication Through Statistical Multiplexing (OneRAN Argument)

The second, and economically more powerful, component of the sharing advantage is the throughput gain from statistical multiplexing of independent traffic flows, already formalized in Equation (2). The trunking efficiency factor $\eta_{trunking} > 1$ reflects the Erlang-B statistical multiplexing gain achieved when independent operator traffic streams are pooled into a shared radio resource.

Sheikh et al. [19] demonstrate this analytically and confirm it with LTE field measurements from three Finnish MNOs, observing that pooled throughput at cell-edge users exceeds the sum of individual operator capacities. This is not merely a theoretical result: the trunking gain means that a single pooled infrastructure can deliver better quality of service to users than three separate infrastructures, at one-third the per-operator cost. In rural contexts, where per-operator site utilization may be 5–15% of nominal capacity during daytime hours, the trunking gain is particularly pronounced.

It is important to note, however, that realizing this gain in practice requires regulatory frameworks that permit full spectrum pooling (MOCN or OneRAN models), which are not universally available. As discussed in Section 5.3 of this review, spectrum licensing policies across jurisdictions vary significantly, and several regulatory environments restrict or prohibit the form of spectrum sharing required to achieve $\eta_{trunking} > 1$ at the radio layer. Where only physical infrastructure sharing is permitted (passive sharing or MORAN), the throughput gain reduces to the trunking gain achievable within each operator's independent spectrum assignment — still positive, but substantially lower than the full OneRAN case.

4.4.3 Synthesis: The Combined Sharing Dividend

The combined economic impact of Open RAN sharing is therefore the product of two complementary effects: (i) cost division proportional to $\frac{1}{N_{MNO}}$, captured in Equation (3), and (ii) throughput amplification proportional to $\eta_{trunking}$, captured in Equation (2). Together, these define a "sharing dividend" that improves both sides of the rural site business case simultaneously — reducing cost per operator while increasing service capacity per unit of infrastructure investment.

The literature reveals a critical gap in translating this theoretical dividend into empirically verified, commercially deployed outcomes. Sheikh et al. [19] acknowledge that their model does not account for transition costs (legal, regulatory, contractual restructuring), governance mechanisms for ongoing cross-operator operations, or the political economy of operators relinquishing independent spectrum control. Otto [20] and Chakraborty [14] describe neutral-host deployment models that partially capture the Equation (3) benefit in commercial practice, but independently audited TCO comparisons between neutral-host Open RAN and independent operator deployment — incorporating the full δ_{coord} range and all transition costs — do not yet appear in the peer-reviewed literature.

Key Implication: The Open RAN sharing advantage is not a single mechanism but a compound economic effect: per-operator cost division ($\propto \frac{1}{N_{MNO}}$) combined with trunking throughput gain ($\eta_{trunking} > 1$). The coordination overhead factor δ , which the O-RAN SMO can reduce through automated multi-tenant orchestration, is the critical variable determining whether the theoretical sharing dividend translates into realized commercial benefit. Governing bodies, operators, and the O-RAN Alliance should prioritize the development of inter-operator SLA frameworks and SMO multi-tenancy specifications that minimize δ in rural neutral-host deployments — this is currently the most significant unresolved technical-commercial interface in the Open RAN sharing model.

4.5 Energy Management and Renewable Integration

Energy is the dominant OPEX component for remote rural sites, with diesel-dependent sites incurring operational costs approximately 35–40% higher than urban counterparts [2, 3]. Addressing energy cost is therefore both a commercial imperative for MNO viability and an environmental sustainability requirement.

The O-RAN Alliance's energy saving feature taxonomy [21] identifies two primary energy reduction domains within the O-RAN architecture: (i) radio/hardware domain, encompassing O-RU transmit power control, antenna/TRX chain scaling, symbol-level muting, and advanced sleep modes; and (ii) compute/cloud domain, encompassing O-Cloud workload placement, CNF scheduling, and energy-aware O-DU scaling. Open RAN's disaggregated software architecture converts previously static hardware energy levers into programmable policies

enforceable at multiple timescales: near-real-time (xApps via E2, sub-second) and non-real-time (rApps via O1/A1, minutes to hours).

Ashfaq and Safdar [9] propose the O-RAN Rapid Transition Protocol (ORTP), a DU-level xApp that optimizes handover margin (HOM) to reduce unnecessary active transmissions while maintaining coverage continuity. Through 5G system-level simulation, the authors demonstrate approximately 20% dynamic power reduction compared with a baseline 3GPP configuration, formalized in Equation (4):

$$E_{save}(\%) = \left[1 - \frac{P_{ORTP(HOM_{low})}}{P_{baseline}} \right] \times 100 \approx 20\% \quad (4)$$

where $E_{save}(\%)$ is the percentage energy saving, $P_{ORTP(HOM_{low})}$ is power consumption under ORTP with a low-HOM configuration, and $P_{baseline}$ is baseline power consumption without optimization.

The ORTP strategy places energy reduction logic at the O-DU level (midway between fronthaul and midhaul), making it deployable without modification to O-RU hardware — a significant advantage for distributed rural sites where hardware upgrades are logistically complex.

Ndikumana et al. [17] propose an integrated renewable-energy and Open RAN architecture for rural FWA, combining solar photovoltaic (PV) generation with battery storage and an SMO-level energy management framework. The energy availability model in Equation (5) captures the site power balance:

$$E_{RE}(t) = \min[\eta_{PV}P_{solar}(t) + E_{batt}(t), P_{site}(t)] \quad (5)$$

$$S_{fuel} = 1 - \frac{E_{grid}}{E_{total}} \quad (6)$$

where $E_{RE}(t)$ is renewable energy utilized at time t , η_{PV} is photovoltaic conversion efficiency, $P_{solar}(t)$ is solar generation, $E_{batt}(t)$ is available battery energy, $P_{site}(t)$ is site power demand, S_{fuel} is the fractional grid/diesel fuel saving, E_{grid} is energy supplied by grid or diesel, and E_{total} is total energy demand over the evaluation period.

The GSMA Intelligence report [2] emphasizes that technical feasibility of renewable energy systems is insufficient without commercially viable financing structures. Mixed energy systems (solar PV, battery, limited genset backup) paired with tower company partnerships, blended finance (grants, concessional loans, carbon-linked revenues), and multi-stakeholder governance are required to make rural renewable rollouts viable at scale.

4.6 Cost Modeling and TCO Framework

A standardized total cost of ownership (TCO) framework for rural Open RAN deployments is conspicuously absent from the published literature — the most significant research gap identified in this review. Existing cost analyses are predominantly vendor-specific, make non-transparent assumptions about site configurations, and do not account for the multi-year evolution of OPEX under different energy, sharing, and automation scenarios.

Fetterolf [5] provides the most widely cited economic analysis, estimating that RAN constitutes 70–80% of total mobile network TCO, and that Open RAN software costs approximately 30% less than proprietary equivalents. However, this analysis does not address rural-specific cost drivers (power, transport, spares logistics, remote management overhead) or multi-vendor integration costs.

The authors propose the following generalized TCO framework for rural Open RAN deployments as a basis for future standardized evaluation:

$$TCO_{rural} = CAPEX_{site} + CAPEX_{infra} + \frac{\sum_{t=1}^T [OPEX_{power}(t) + OPEX_{transport}(t) + OPEX_{O\&M}(t)]}{(1+r)^t} \quad (7)$$

where TCO_{rural} is the lifecycle cost over the planning horizon; $CAPEX_{site}$ covers tower, O-RU, power-system, and civil-work deployment; $CAPEX_{infra}$ covers shared core, aggregation, and transport infrastructure; $OPEX_{power}(t)$, $OPEX_{transport}(t)$, and $OPEX_{O\&M}(t)$ are time-dependent operational costs; r is the discount rate; and T is the planning horizon in years.

Rural Viability Constraint

The ARPU viability inequality introduced in Equation (8) frames the fundamental tension between the lifecycle cost of rural connectivity infrastructure and the revenue-generating capacity of the population it is intended to serve:

$$ARPU \geq ARPU_{th} = \left(\frac{TCO_{rural}}{N_{subs}} \right) (1 + \mu) \quad (8)$$

$$S_{user} = \max(0, ARPU_{th} - ARPU), \quad S_{total} = N_{subs} \times S_{user} \quad (9)$$

where ARPU is average revenue per user, $ARPU_{th}$ is the viability threshold, TCO_{rural} is the total cost of ownership, N_{subs} is the subscriber base, μ is the target margin, S_{user} is the required subsidy per user, and S_{total} is the total subsidy requirement. The feasibility condition is satisfied when ARPU meets or exceeds $ARPU_{th}$; otherwise, public subsidy, mandated sharing, or blended finance is required.

This inequality is deceptively simple but encodes the entire commercial logic of rural mobile deployment. Its components warrant detailed examination.

4.6.1 Revenue-Side Constraints

ARPU in rural and remote markets is structurally constrained by household income levels, purchasing power parity, and the price sensitivity of first-time mobile subscribers. In sub-Saharan Africa — the region with the largest rural unconnected population — rural ARPU for mobile broadband services typically ranges from USD 1.50 to USD 4.00 per month, compared to USD 6.00–15.00 in urban centers of the same countries [3, 4]. This 2–5× urban-rural ARPU differential is not primarily a function of willingness to pay for connectivity (which evidence suggests is high relative to income) but of absolute income constraints and the price-sensitivity of demand at low income levels.

GSMA Intelligence [3] projects that rural ARPU in the lowest-income markets may not rise above USD 2.50–3.00 for the foreseeable planning horizon, even with sustained GDP growth and mobile penetration expansion. This effectively sets a ceiling on the left-hand side of the viability inequality that is unlikely to be materially altered by technology choices alone.

4.6.2 Cost-Side Constraints

The right-hand side of Equation (8) — $\left(\frac{TCO_{rural}}{N_{subs}} \right) \times (1 + \text{margin})$ — is the cost per subscriber amortized over the deployment lifetime, scaled by a required profit margin. Both TCO_{rural} (from Equation (7)) and N_{subs} are unfavorable in rural contexts relative to urban deployments.

TCO_{rural} is elevated by rural-specific cost premiums: site access and civil works in difficult terrain; power systems (solar/battery/genset) replacing absent grid connections; backhaul infrastructure (satellite terminals, TVWS equipment) replacing absent fiber; and higher O&M costs from remote logistics and infrequent maintenance visits. Fetterolf [5] estimates that RAN constitutes 70–80% of total mobile network TCO, and GSMA data indicates that rural sites cost 35–40% more to operate than urban equivalents on a per-site basis [3].

N_{subs} — the subscriber base per site — is constrained by population density. Rural sites in sub-Saharan Africa or South Asian remote regions may serve 500–2,000 potential subscribers within their coverage footprint, compared to 5,000–50,000 for urban sites. The combination of elevated TCO_{rural} and depressed N_{subs} drives cost per subscriber to levels that can exceed USD 5–15 per month before margin — structurally above the ARPU ceiling identified above.

4.6.3 The Viability Gap and Implications for Open RAN Strategy

The structural violation of Equation (8) — $ARPU < \text{cost threshold}$ — in most rural deployment scenarios is not a temporary market failure that technology improvements will automatically resolve. It is a persistent structural condition arising from the geography of poverty and connectivity: the populations furthest from connectivity are also those with the lowest incomes and the smallest subscriber bases per unit of infrastructure investment.

Open RAN addresses this structural gap through three mechanisms, each of which acts on a different component of the viability inequality:

- (i) Reducing TCO_{rural} : Through vendor competition in the open ecosystem (estimated 30% software cost reduction [5]), multi-vendor sourcing flexibility, and energy optimization (ORTP ~20% power reduction [9], SMO automation ~10% OPEX reduction [16]).
- (ii) Increasing effective N_{subs} per unit of infrastructure cost: Through infrastructure sharing (Equation (3)), which distributes fixed site costs across multiple MNOs' subscriber bases, effectively multiplying N_{subs} by N_{MNO} for cost allocation purposes.

(iii) Enabling subsidy targeting: Open RAN's standardized interfaces and cost transparency make it significantly easier for regulatory authorities and development finance institutions to design and verify universal service fund (USF) subsidies, cost-based interconnection rates, and output-based aid programs. Proprietary RAN, with its opaque vendor-specific cost structures, makes efficient subsidy design substantially more difficult.

However, Equation (8) also makes clear that none of these mechanisms is individually sufficient to close the viability gap in the most remote and lowest-ARPU environments. The mathematics of the constraint — with ARPU bounded below USD 3.00 and cost per subscriber above USD 8.00 in extreme cases — implies that a combination of all three mechanisms, plus direct public subsidy or alternative revenue models (e.g., enterprise/government anchor tenants, carbon credits for rural electrification co-benefit), is required [2, 17].

Key Implication: Equation (7) is the governing constraint of rural mobile deployment economics. Open RAN improves the right-hand side of this inequality through cost reduction and sharing, but does not resolve the fundamental viability gap in the most remote markets. Policy instruments — USF subsidies, spectrum awards conditioned on rural coverage obligations, blended finance — are not optional supplements to Open RAN deployment; they are mathematically necessary conditions for commercial viability in the lowest-ARPU rural markets. Academic research should prioritize empirically grounded, standardized TCO models that make the magnitude of this gap precisely quantifiable across deployment scenarios, enabling evidence-based public subsidy design.

The preceding models establish the economic and technical basis for load-adaptive energy efficiency, which is discussed next.

Load-Adaptive Energy Efficiency

The energy consumption profile of a rural Open RAN site is fundamentally non-linear with respect to traffic load. Unlike copper-era or even early 4G base stations, which consumed near-constant power regardless of offered traffic, modern disaggregated O-RAN architectures expose programmable control points across the O-RU, O-DU, and O-Cloud layers that allow energy expenditure to be modulated in proportion to instantaneous demand. This property — load-adaptive energy efficiency — is not merely a desirable feature in urban deployments but a commercial necessity for unattended, off-grid rural sites where every watt-hour has a direct operational cost.

4.6.4 Physical Interpretation of the Load Factor $\alpha_{load(t)}$

The OPEX power decomposition introduced in Equation (10) separates site power consumption into two regimes governed by the time-varying load factor $\alpha_{load(t)} \in [0, 1]$:

$$OPEX_{power(t)} = P_{TRX}\alpha_{load(t)} + P_{idle}[1 - \alpha_{load(t)}] + P_{cooling} + P_{bh} \quad (10)$$

where $OPEX_{power(t)}$ is the power-related cost or consumption proxy at time t , P_{TRX} is transmit power at full load, P_{idle} is idle/base power consumption, $\alpha_{load(t)}$ is the traffic load factor, $P_{cooling}$ is cooling-system consumption, and P_{bh} is the backhaul power overhead for TVWS, satellite, or microwave transport.

When $\alpha_{load(t)}$ approaches zero — a condition that is disproportionately common in rural and remote deployments, which exhibit both low mean traffic volumes and pronounced day-night asymmetry — the site power consumption converges toward the idle power floor P_{idle} . This idle power floor represents the irreducible consumption of active electronics, cooling systems, and backhaul termination equipment maintained even when no user traffic is being served. In conventional proprietary base stations, this floor is largely fixed in hardware and cannot be reduced through software policy. The O-RAN architecture changes this fundamentally.

In the O-RAN disaggregated model, P_{idle} is itself a controllable variable. The O-RAN Alliance's energy saving feature taxonomy [21] defines a hierarchy of sleep modes at the O-RU level — from symbol-level muting (sub-millisecond timescale, highest granularity) through carrier shutdown (seconds) to deep sleep (minutes to hours) — each associated with progressively deeper reductions in P_{idle} at the cost of increasing wake-up latency. For rural sites serving sparse populations with predictable low-traffic periods (e.g., late night hours, agricultural off-seasons), deeper sleep modes become viable without violating latency or availability service level agreements.

4.6.5 RIC-Based Energy Control as the Enabling Mechanism

The practical realization of load-adaptive energy efficiency requires a control architecture capable of predicting $\alpha_{load(t)}$ with sufficient accuracy to engage and disengage sleep modes without degrading user experience. This is precisely the function of the Near-RT RIC xApp layer operating via the E2 interface, and the Non-RT RIC rApp layer operating via the O1/A1 interface stack [21].

Ashfaq and Safdar [9] provide direct empirical quantification of this dynamic through ORTP. Their system-level 5G simulation demonstrates that a DU-level xApp can reduce dynamic RAN power consumption by approximately 20%, as formalized earlier in Equation (4).

The significance of ORTP for rural deployment is its architectural placement. By operating at the O-DU level — midway between fronthaul and midhaul — ORTP does not require hardware modifications to the O-RU, nor does it demand the ultra-low-latency E2 response times associated with near-PHY xApps. This makes it deployable over the constrained midhaul transport links characteristic of rural regional edge architectures, where O-DU is placed at a regional edge node and communicates with the Near-RT RIC over a non-ideal transport path [1, 9, 11].

At the Non-RT RIC level, rApps can extend this optimization across longer timescales: training ML models on historical $\alpha_load(t)$ patterns to generate predictive sleep schedules, building site-specific energy profiles that account for seasonal agricultural traffic cycles or community event patterns, and pushing A1 policies that pre-position Near-RT RIC xApps for anticipated low-load periods. This multi-timescale control architecture — Sub-second (xApp/E2) → Minutes (rApp/A1) → Hours (SMO/O1) — represents a qualitative advance over the static energy management available in proprietary RAN equipment.

4.6.6 Implications for Rural Site Economics

The economic significance of the $\alpha_load(t)$ term in Equation (10) is amplified in rural contexts by the high marginal cost of energy. Remote sites dependent on diesel generation face fuel costs of USD 0.40–1.20 per kWh at the point of consumption — three to eight times higher than grid electricity tariffs in the same country [2, 3]. A 20% reduction in dynamic power consumption, as demonstrated by ORTP [9], therefore translates to a proportionally larger OPEX reduction in absolute monetary terms for a rural diesel-dependent site than for an urban grid-connected site with identical load profiles.

Furthermore, when load-adaptive energy efficiency is combined with solar PV and battery storage (as in Equation (5)), the reduction in peak power demand has a compounding effect: lower peak consumption reduces the required solar panel capacity and battery bank sizing, in turn reducing upfront CAPEX for the off-grid power system. This non-linear interaction between energy efficiency and renewable system sizing represents an underexplored optimization dimension in the rural Open RAN literature. Ndikumana et al. [17] model a related joint optimization for FWA scenarios, but a generalized multi-site, multi-technology model incorporating the full Equation (10) decomposition remains an open research gap.

Key Implication: In rural Open RAN deployments, where $\alpha_load(t)$ is near zero for extended daily periods and energy costs are 3–8× higher than urban equivalents, load-adaptive RIC-based sleep mode control is not an optional optimization feature but a prerequisite for OPEX sustainability. The ~20% dynamic power reduction demonstrated by ORTP [9] should be treated as a conservative lower bound achievable with single-xApp deployment; coordinated multi-xApp strategies targeting symbol muting, TRX chain scaling, and predictive sleep scheduling are expected to yield higher aggregate savings in operationally validated multi-vendor deployments.

5. DEPLOYMENT CHALLENGES AND BARRIERS

5.1 Infrastructure and Cost Barriers

Rural sites are capital-intensive relative to their revenue potential. GSMA Intelligence [3] reports that rural sites cost approximately 35–40% more to operate than urban counterparts, primarily because of transport, power, and remote maintenance costs. The compounding effect of rural ARPU, typically 2–5 times lower than urban ARPU in sub-Saharan Africa and South Asia, means that conventional single-operator site economics often require public subsidy or alternative commercial models to become viable.

Open RAN introduces additional upfront integration costs not present in proprietary RAN deployments. Multi-vendor integration requires qualified interoperability testing through Open Testing and Integration Centers (OTICs), procurement of system integration services, and ongoing multi-vendor network management complexity. Azariah et al. [6] survey the Open RAN challenge landscape, identifying multi-vendor integration, security, and performance consistency as the three most significant deployment barriers, all of which are amplified in rural contexts where local technical expertise is scarce.

5.2 Technical Limitations

The scarcity of ruggedized, multi-band O-RUs capable of operating at low-band frequencies (600–900 MHz) with simultaneous mid-band capability represents a significant hardware gap for rural Open RAN. Low-band coverage is essential for achieving the coverage radii required to serve sparse rural populations cost-effectively, but the

current Open RAN equipment ecosystem is dominated by mid- and high-band O-RUs optimized for urban capacity deployments [1, 8].

Constrained or high-latency backhaul directly constrains the feasible functional split options. As formalized in Equation (1), Option 7.2x is often unsuitable over satellite or multi-hop microwave links unless the O-DU is co-located near the O-RU or dedicated low-latency transport is available. This assessment should not be read as a universal rejection of Option 7.2x in rural networks, because its transport demand depends strongly on bandwidth, antenna order, compression, numerology, synchronization, and sectorization. In many remote scenarios, however, the backhaul environment forces deployments toward higher-layer splits (Options 1-2), which push more processing closer to the radio site and reduce the benefits of centralization [1, 10, 12].

5.3 Regulatory and Policy Barriers

Spectrum policy is identified as the most consequential single policy lever for rural Open RAN economics [13]. The availability of long-term, affordable low-band spectrum assignments substantially improves rural site business cases. Regulatory frameworks for spectrum pooling (MOCN) and neutral-host models vary significantly across jurisdictions and can prevent or delay implementation of the most economically efficient sharing models [3].

Security and supply chain concerns in several jurisdictions have introduced procurement restrictions that disfavor multi-vendor or third-party neutral-host deployments — directly conflicting with Open RAN's architectural rationale [22, 23]. Singleton [22] recommends alignment of security testing with industry certification frameworks and risk-based approaches that balance security with vendor diversity, but implementation of such frameworks varies considerably across regulatory environments.

6. COMPARATIVE ANALYSIS OF DEPLOYMENT STRATEGIES

Table 4 provides a consolidated comparative evaluation of the eight deployment strategy configurations identified in the literature, integrating architecture, infrastructure, quantitative performance evidence, and limitation assessments.

Table 4. Comparative Evaluation of Open RAN Deployment Strategies for Rural and Remote Contexts

Deployment Model	Scenario	Infrastructure	Key Benefits	TCO Impact	Limitations / Open Issues
Cloud-native Greenfield O-RAN	New rural projects with operator control [1, 8, 15]	Regional edge cloud; Fiber/ μ wave; Solar+battery	Vendor diversity; automation; CI/CD agility; zero-touch provisioning	CAPEX $\uparrow$ (cloud infra); OPEX $\downarrow$ 10–20% [16]	Requires cloud ops expertise; upfront integration risk; limited long-term multi-vendor field data
Brownfield Overlay O-RAN	Established operators with legacy RAN [14, 24]	Reuse existing backhaul; satellite for last hop	Phased investment; minimal disruption	Moderate CAPEX; limited short-term OPEX gain	Legacy vendor lock-in; interface mapping complexity; dual-stack operations burden
Neutral Host – MOCN	Multi-MNO rural clusters; public infrastructure [19, 20]	Shared backhaul; pooled power (solar/genset)	CAPEX/OPEX shared; improved spectrum utilisation	CAPEX $\downarrow$ 30–50% per operator (theoretical) [19]	Inter-PLMN orchestration; complex SLAs; governance gaps; spectrum licensing constraints
Neutral Host – MORAN	RAN sharing with spectrum isolation [20]	Shared physical RAN; separate spectrum allocations	Simpler ops vs MOCN; reduced integration risk	CAPEX $\downarrow$ moderate	Lower spectral efficiency; regulatory compliance overhead
Satellite-Enabled Micro Sites	No terrestrial backhaul [12]	LEO/MEO/GEO terminals; local O-RU; solar	Rapid deployment; ubiquitous reach; near-instant coverage	High terminal CAPEX; ongoing satellite OpEx	Latency-split constraints (NTN); handover complexity; LEO constellation coverage gaps
Edge-Consolidated DU/CU + SMO/RIC	Regional clusters; low-latency loops [1, 11]	Regional edge cloud; resilient backhaul; solar+backup	Low-latency control; energy optimization; automation	OPEX $\downarrow$ ~10% [16]; power $\downarrow$ ~20% [9]	Edge infra CAPEX; skilled cloud ops requirement; fronthaul capacity constraints
OneRAN – Full Pooling	Highway/rural multi-operator pooling [19]	Fully shared RAN + spectrum; pooled transport	Multiplicative throughput gain; reduced mast count	CAPEX/OPEX $\downarrow$ significantly (modelled)	Regulatory/legal barriers; spectrum licensing; inter-operator governance unsolved
TVWS + Low-Power O-RAN	Deep rural; unlicensed backhaul [8]	TVWS backhaul; low-power O-RU; solar	Field feasibility demonstrated; attractive propagation for deep rural coverage	Potentially low CAPEX/OPEX, but not yet proven by audited multi-year data	TVWS interference management; limited regulatory frameworks; no public long-term OPEX, availability, traffic, or churn data

Sources: synthesized from [1, 2, 6, 7, 8, 9, 12, 15, 16, 17, 19, 20]. TCO Impact: $\uparrow$ = increase; $\downarrow$ = decrease. Quantitative figures are from cited sources; ranges indicate variation across scenarios.

Table 5 synthesizes the quantitative KPI evidence extracted from the reviewed literature while explicitly separating peer-reviewed evidence from standards documents, vendor white papers, operator reports, and pilot/industry cases. This separation is important because the maturity, reproducibility, and independence of the evidence differ substantially across source types.

Table 5. Quantitative KPI Evidence from Reviewed Studies, Separated by Evidence Class

Study / Source	Technology	Energy Saving	Throughput Gain	Backhaul / Split	Validation Method
Peer-reviewed evidence					
Ashfaq & Safdar [9]	ORTP (O-DU xApp)	~20% dynamic power reduction	Cell-edge improvement reported	5G NR; DU-level split; midhaul	System-level simulation
Sheikh et al. [19]	OneRAN full pooling	N/A (CAPEX focus)	Multiplicative gain at cell edge	52 km highway LTE corridor	Field measurement + modelling
Ndikumana et al. [17]	Renewable + Open RAN FWA	Diesel elimination / reduced fossil-fuel dependence modelled	Rural FWA baseline met	Fiber/satellite hybrid	Analytical optimization model
Seeram et al. [12]	LEO NTN + O-RAN split	N/A	Handover delay modelled	Regenerative LEO; midhaul	Analytical / simulation
Zhang et al. [25]	ARA-O-RAN living lab	N/A	Programmable rural/agricultural testbed capabilities	End-to-end O-RAN living lab	Experimental testbed / workshop paper
Standards, vendor, operator, and industry/pilot evidence					
Niklasson et al. [16]	SMO automation (brownfield)	~10% OPEX reduction over 5 yr	N/A (OPEX study)	Multi-vendor O-RAN stack	Ericsson white paper / analytical claim
NuRAN / GSMA Pilot [8]	Low-power O-RAN + TVWS	Solar-powered field feasibility reported	Early uptake described; detailed KPIs not disclosed	TVWS backhaul; solar power	Industry pilot case (Ghana)
O-RAN Alliance [21]	Energy features (rApps/xApps)	Multi-domain energy reduction mechanisms specified	No degradation targeted	RU sleep modes; cloud scaling	Specification / use-case analysis
DISH Network [15]	Cloud-native vRAN (Mavenir)	N/A (greenfield)	Commercial vRAN KPIs reported by operator/vendor	Fiber backhaul; O-CU cloud	Operator/vendor deployment report

Sources: as cited. N/A = not reported in the respective study. The table separates peer-reviewed evidence from grey literature and industry/pilot reports; quantitative figures from vendor or industry sources should be treated as deployment claims requiring independent field validation.

The comparative analysis reveals several important cross-cutting observations. First, quantitative evidence remains heavily concentrated in simulation and analytical studies, with limited peer-reviewed field measurement data. The Sheikh et al. [19] highway corridor study provides field measurement and modelling evidence, while the NuRAN/GSMA Ghana pilot [8] provides useful field-feasibility evidence but lacks comprehensive technical and commercial KPI disclosure. Second, energy reduction claims (20% via ORTP [9]; 10% OPEX reduction via SMO [16]) are derived from simulation, analytical, vendor, or single-technology studies and have not yet been validated across long-term multi-vendor rural deployments. Third, TCO analyses are fragmented and non-comparable due to inconsistent scope, discount rates, and OPEX component definitions, confirming the urgent need for a standardized rural Open RAN TCO framework.

7. INTEGRATED OPTIMIZATION FRAMEWORK FOR RURAL OPEN RAN

The compact optimization form synthesizes the individual analytical expressions into a unified constrained optimization problem for rural Open RAN deployment:

$$\text{minimize } TCO_{\text{rural}}(\text{split}, \text{backhaul}, N_{\text{MNO}}, E_{\text{RE}}, x_{\text{App}}) \quad (11)$$

$$\text{subject to: } ARPU + S_{\text{user}} \geq \left(\frac{TCO_{\text{rural}}}{N_{\text{subs}}} \right) (1 + \mu); \quad L_{fh}(\text{split}) \leq L_{\text{max}}(\text{split}); \quad \text{and } E_{\text{RE}}(t) + E_{\text{grid}}(t) \geq P_{\text{site}}(t).$$

This formulation encodes a multi-dimensional, multi-timescale, and multi-stakeholder optimization problem. It links architectural choices, backhaul selection, sharing degree, energy autonomy, and RIC-based automation to the central feasibility condition for rural deployment.

7.1 Structure of the Optimization Problem

The objective function minimizes TCO_{rural} as defined in Equation (7), while commercial feasibility is governed by the viability and subsidy condition in Equation (8).

Each term in this sum represents a distinct optimization sub-problem with its own feasible solution set and its own set of controlling decision variables. $CAPEX_{site}$ is minimized through site sharing (Equation (3)), reducing it by factor $\frac{1}{N_{MNO}}$ for shared deployments. $OPEX_{power}$ is minimized through load-adaptive energy control (Equations (10) and (4)) and renewable integration (Equation (5)). $OPEX_{transport}$ is minimized through backhaul technology selection (fiber/microwave/satellite/TVWS) matched to the functional split choice (Equation (1)). $OPEX_{O\&M}$ is minimized through SMO/RIC automation — zero-touch provisioning, remote fault management, and automated performance optimization — reducing the requirement for on-site technical personnel [6, 16].

The viability constraint — $ARPU \geq \text{cost threshold}$ — is not a design choice but a boundary condition imposed by the market environment. It defines the feasible region of the optimization: any solution in which $\frac{TCO_{rural}}{N_{subs}} \times (1 + \text{margin}) > ARPU$ is commercially infeasible without external intervention (subsidy, as in Point 4). The optimization problem is therefore one of finding the minimum TCO_{rural} solution that lies within the feasible region — or, when no such solution exists, of determining the minimum required subsidy to render the problem feasible.

7.2 Decision Variables by Stakeholder Class

The power of the compact optimization formulation is that it clarifies which decision variables are controlled by which stakeholder class, enabling a precise mapping of responsibilities in the rural Open RAN deployment ecosystem:

MNOs and Towercos control the architectural decisions that directly determine TCO_{rural} : functional split selection (Equation (1)), backhaul technology mix, sharing model (Equations (3) and (2)), energy system design (Equations (10) and (5)), and the degree of SMO/RIC automation deployed (Equation (4)). These decisions collectively define the cost structure of the deployment.

Regulators and Policymakers control the boundary conditions of the optimization: spectrum allocation policy determines the N_{MNO} feasible for sharing models; USF policy determines the subsidy available when $ARPU < \text{threshold}$; procurement rules determine whether Open RAN multi-vendor configurations are eligible for subsidized deployment; and spectrum pricing determines a component of $OPEX_{transport}$.

Vendors and System Integrators control the unit economics of the objective function components: O-RU hardware cost and power efficiency determine $CAPEX_{site}$ and $OPEX_{power}$ respectively; integration toolchain maturity determines the hidden CAPEX of multi-vendor deployment; and xApp/rApp ecosystem richness determines the achievable E_{save} from RIC automation.

Development Agencies and Funders provide the financial instruments — grants, concessional loans, guarantees, carbon credits — that shift the viability constraint, enabling deployment in markets where $ARPU < \text{threshold}$ even under the most cost-optimized Open RAN configuration.

7.3 Analytical Significance of the Compact Form

The compact optimization form is analytically powerful precisely because it makes explicit what extensive qualitative literature often obscures: the rural Open RAN deployment problem has a single objective (minimize cost) and a single binding constraint (commercial viability), but is governed by decision variables spread across four distinct stakeholder classes operating on different timescales and with different incentive structures. This stakeholder-decision variable mapping reveals that no single actor can solve the optimization unilaterally.

An MNO that minimizes TCO_{rural} through optimal architectural choices cannot overcome an unfavorable ARPU constraint in a low-income rural market without regulatory intervention. A regulator that mandates sharing to increase N_{subs} per unit of infrastructure cost cannot compel vendors to produce the ruggedized low-power O-RUs needed to minimize $OPEX_{power}$. A development finance institution that provides subsidy to render $ARPU \geq \text{threshold}$ cannot guarantee that the MNO will deploy an Open RAN architecture that is technically optimized for the deployment context. The optimization problem is jointly feasible only when all four stakeholder classes act in coordination — a governance challenge that is, in the authors' assessment, as significant as any of the technical challenges identified in this review.

Ndikumana et al. [17] make the closest approach to a formal solution of this joint optimization for a specific renewable-powered FWA scenario, formulating it as a MINLP. Zhang et al. [25] demonstrate an operational instantiation of the multi-stakeholder coordination requirement through the ARA-O-RAN living laboratory for agricultural and rural communities, which explicitly incorporates technology, governance, and community stakeholder dimensions within a single experimental framework. These contributions are valuable but represent single-scenario solutions; a generalized, empirically parameterized solution to the compact optimization problem across diverse rural deployment contexts does not yet exist in the literature.

7.4 Extensions and Future Formulations

The compact form as presented is a single-period, single-site formulation. Extensions required for practical deployment planning include:

Multi-site, multi-period optimization: Rural deployments are not single-site decisions but network-level investment programs spanning multiple sites, phased rollout sequences, and evolving traffic demand. The objective function should be extended to $\sum_j \sum_t TCO_{rural(j,t)}$ over sites j and periods t , with inter-site dependencies captured through shared backhaul infrastructure and SMO-managed radio resource pooling across sites.

Stochastic formulation: Key parameters — ARPU, $\alpha_{load(t)}$, $P_{solar(t)}$, satellite link availability — are stochastic. A robust optimization formulation that maintains viability under adverse realizations of these parameters (e.g., extended cloudy seasons, satellite link outages, ARPU decline) is required for reliable deployment planning in rural contexts where risk buffering capacity is limited [17].

Socioeconomic impact extension: The optimization as stated maximizes commercial efficiency. A social welfare formulation would add a socioeconomic benefit term to the objective — capturing education, health, agriculture, and commerce co-benefits of connectivity — weighted by a social discount rate that reflects the public value of universal connectivity beyond its commercial returns. This extension is essential for justifying public subsidy in terms that development finance institutions can incorporate into their investment appraisal frameworks [3].

Key Implication: The compact optimization form "minimize TCO rural subject to $ARPU \geq \text{cost threshold}$ " is more than a mathematical convenience — it is a governance roadmap. It specifies exactly which actors must contribute which decisions to render rural Open RAN deployment commercially and technically feasible, and makes explicit that no single actor can solve the problem alone. Future research should prioritize empirically parameterized, multi-site, multi-period, and stochastic extensions of this formulation, incorporating socioeconomic benefit terms, to provide the analytical foundation for evidence-based public investment in rural Open RAN deployment programs.

8. STAKEHOLDER RECOMMENDATIONS

8.1 For Policymakers and Regulators

Regulatory frameworks that enable infrastructure sharing must be prioritized. Clear legal and technical frameworks for neutral-host deployments — including spectrum pooling (MOCN), MORAN, and full pooling (OneRAN) models — are essential prerequisites for unlocking operator participation in rural deployment programs. Spectrum pricing policy should provide long-term assignment certainty and afford cost structures for low-band spectrum that reflect its social value in rural contexts [3, 13].

Blended finance mechanisms that combine telecommunications investment with renewable energy funding should be institutionalized. Rural site OPEX is dominated by energy costs; grant programs, concessional loans, and carbon credit mechanisms that lower the financial risk of renewable energy deployment can materially improve the rural Open RAN business case [2, 17].

Regulators should align security certification frameworks with Open RAN's multi-vendor reality. Risk-based procurement frameworks that enable vendor diversity while maintaining security assurance — as recommended by Singleton [22] and the UK government's Telecoms Supply Chain Diversification program — provide a model applicable across jurisdictions.

8.2 For Mobile Network Operators and Towercos

Rural Open RAN deployment should be piloted in isolated, manageable clusters - geographically defined rural coverage zones where existing legacy RAN interdependencies are minimal - before broader migration. Orange's Romania deployment model [26] demonstrates that hybrid approaches (Open RAN in rural clusters and legacy RAN in urban/macro markets) reduce migration friction and allow independent performance validation. Similarly, small-scale rural Open RAN site deployments, such as church-based mobile sites in the United Kingdom [27],

illustrate how community infrastructure can support practical coverage extension. Living-laboratory environments with comprehensive KPI collection protocols are recommended as precursors to commercial rollout.

RIC-based energy and mobility optimization should be deployed as a priority operational investment. ORTP-style xApps and SMO energy rApps provide measurable OPEX reduction with minimal capital outlay, improving site cash flow and extending the commercial lifetime of rural investments [9, 16].

8.3 For Vendors and System Integrators

The rural Open RAN equipment ecosystem requires purposeful development of ruggedized, multi-band, low-power O-RUs with integrated low-band (700/850/900 MHz) and mid-band capability, simplified zero-touch provisioning (ZTP) for unattended site deployment, and validated interoperability stacks tested in OTIC environments [1, 6, 8, 24]. Energy per transmitted byte - rather than peak throughput alone - should be adopted as a primary design criterion for rural O-RU hardware.

Investment in OTIC qualification programs and open-source integration toolchains (e.g., O-RAN Software Community contributions) will reduce integration risk and time-to-deployment for multi-vendor rural pilots, accelerating the accumulation of field evidence required to mature the rural Open RAN business case.

8.4 For Development Agencies and Funders

Proof-of-concept programs that combine neutral-host business models, renewable power, local capacity building, and socioeconomic KPI measurement should be supported as the primary evidence-generation mechanism for rural Open RAN. Development finance institutions (DFIs) and multilateral donors should require that rural connectivity pilots disclose comprehensive technical and commercial KPIs - including CAPEX, OPEX, site availability, traffic growth, revenue, churn, throughput, maintenance cost, and community outcome metrics - as a condition of funding. The current opacity of pilot results, exemplified by the NuRAN/GSMA Ghana pilot [8], limits the external evidence base and constrains future investment decisions.

9. POLICY INSIGHT: SUBSIDY TRIGGER AND PUBLIC INVESTMENT CONDITIONS

Building directly on the viability constraint of Equation (8), the policy insight encodes a formal trigger condition for public intervention in rural mobile markets. When ARPU falls below the cost threshold — that is, when the commercial viability condition is violated — the inequality prescribes that one or more of three corrective mechanisms becomes necessary: Universal Service Fund (USF) subsidy, government infrastructure grants, or infrastructure sharing mandates. This is not a normative policy recommendation but an arithmetic consequence of the cost structure of rural mobile connectivity.

9.1 Formalizing the Subsidy Trigger

The subsidy trigger condition can be stated precisely by expressing the per-user and total subsidy requirement over a consistent revenue period:

$$S_{total} = T_{years} \times N_{subs} \times \max(0, ARPU_{th} - ARPU) \quad (12)$$

where S_{total} is the total subsidy required over the planning period, T_{years} is the deployment lifetime, N_{subs} is the subscriber base, $ARPU_{th}$ is the viability threshold defined in Equation (8), and ARPU must be measured using the same time unit as the threshold. If ARPU is monthly, the expression should be annualized by multiplying the monthly gap by 12 before applying T_{years} .

9.2 Universal Service Funds and Their Structural Limitations

USF mechanisms — in which a levy on telecommunications revenues is ring-fenced for rural coverage investment — are the most widespread policy instrument for addressing the rural viability gap. GSMA analysis [3, 4] documents USF programs across more than 100 jurisdictions, with annual disbursements ranging from tens of millions to hundreds of millions of USD. However, the effectiveness of USF programs is highly variable, with several structural limitations that the Open RAN architecture can help address.

First, USF subsidy design historically suffers from information asymmetry: regulators cannot independently verify the actual TCO of a rural site because proprietary RAN equipment vendors do not disclose cost structures. Open RAN, with its commodity hardware components, open-source software options, and competitive multi-vendor procurement, provides regulators with sufficient cost transparency to design output-based subsidies calibrated to verifiable cost benchmarks rather than unverifiable vendor-claimed deployment costs [22, 23].

Second, USF programs frequently impose technology-neutral or technology-specific conditions that inadvertently favor legacy proprietary RAN. Procurement frameworks designed for single-vendor integrated base station deployment may exclude multi-vendor Open RAN configurations on the basis of interoperability certification requirements or security evaluation criteria that have not been updated to reflect the Open RAN vendor diversity model. Singleton [22] recommends risk-based procurement frameworks as the appropriate resolution, aligning security testing with industry certification to enable Open RAN participation in subsidized rural programs.

Third, USF disbursement is often sequential (capital grant followed by performance-based payments) in ways that are misaligned with the Open RAN deployment cycle, which front-loads integration and commissioning costs. Blended finance structures — combining USF capital grants with concessional loans for ongoing OPEX support and performance-based payments tied to verified coverage and throughput KPIs — are better aligned with the Open RAN cost profile, as discussed by GSMA Intelligence [2] in the context of renewable energy co-investment.

9.3 Government Infrastructure Investment as Direct Intervention

In markets where ARPU is structurally below the minimum commercially viable threshold even under the most favorable Open RAN sharing and energy optimization scenarios, direct government infrastructure ownership — analogous to public road or electrical grid investment — may be the appropriate policy instrument. Under this model, the government funds and owns passive and active rural infrastructure (towers, power systems, and potentially O-RU and O-DU equipment), leasing wholesale access to MNOs at cost-based rates that allow commercial ARPU-based service delivery on a viable basis.

The neutral-host model, as described by Otto [20] and Chakraborty [14], represents a commercially structured approximation of this approach, in which a private neutral-host operator rather than government provides the shared infrastructure. The O-RAN architecture is well-suited to neutral-host government infrastructure investment because its open interfaces allow government-owned infrastructure to be operated under independent management while hosting commercially competing MNO tenants — a separation that is difficult to implement with proprietary vendor-specific equipment requiring single-vendor management systems.

9.4 Infrastructure Sharing as Regulatory Mandate

The third corrective mechanism — mandated infrastructure sharing — represents the regulatory exercise of compulsion where voluntary sharing does not emerge from market dynamics alone. Several jurisdictions have introduced mandatory RAN sharing obligations for rural coverage areas as conditions of spectrum license awards, requiring licensees to share active RAN infrastructure with competitors in defined geographic zones as a condition of retaining spectrum rights [13].

Open RAN facilitates compliance with such mandates by providing the technical architecture for multi-tenant RAN sharing without requiring the participating operators to adopt common proprietary vendor equipment. Each MNO can maintain its preferred software stack and core network integration while sharing physical infrastructure, because the O-RAN open interfaces provide the clean separation layer between physical hardware and operator-specific network functions. This technical capability does not eliminate the commercial and governance challenges of mandated sharing, but it removes the technical barriers that have historically made active RAN sharing between competing operators with different vendor ecosystems practically infeasible.

Alam et al. [7] note that end-to-end slicing in O-RAN — spanning RAN, transport, and core network domains — provides the technical mechanism for enforcing per-operator service isolation in a shared physical infrastructure, including the performance guarantees (minimum throughput, maximum latency, availability) that regulatory mandated sharing frameworks require in their SLA provisions. The standardization of these slicing mechanisms across O-RAN Alliance, 3GPP, and ETSI frameworks remains incomplete, however, and represents a priority area for standards development before mandated sharing can be reliably implemented in commercial rural Open RAN deployments.

9.5 Implications for African Rural Connectivity

For African rural connectivity, the analysis suggests that Open RAN should be positioned less as a stand-alone equipment substitution and more as a platform for coordinated rural-infrastructure policy. The most relevant deployment combination is likely to involve low-band spectrum for wide-area coverage, shared neutral-host or tower-company infrastructure, solar/battery-powered sites, microwave/LEO/TVWS hybrid backhaul, and SMO/RIC automation to reduce field maintenance. In low-ARPU communities, this architecture should be paired

with Universal Service Fund support, concessional finance, government anchor-tenancy demand, and local maintenance capacity building. The Ghana TVWS/NuRAN case is therefore best interpreted as an African field-feasibility signal, not as a complete commercial proof; future African pilots should publish OPEX, availability, revenue, traffic, churn, and community-impact metrics to support evidence-based scale-up.

Key Implication: The subsidy trigger condition derived from Equation (7) transforms the rural connectivity policy debate from a qualitative argument about market failure into a quantitative engineering problem: given a measured ARPU ceiling, a verifiable Open RAN TCO profile, and a defined sharing model, the required public subsidy quantum can be calculated with precision. This quantitative framing should be adopted by telecommunications regulators, USF administrators, and development finance institutions as the basis for evidence-based rural connectivity investment decisions. Open RAN's cost transparency and sharing architecture are the technical prerequisites that make this quantitative approach feasible.

10. RESEARCH GAPS AND FUTURE DIRECTIONS

This systematic review identifies eight significant research gaps that require targeted investigation to advance the evidence base for rural Open RAN deployment. These gaps are summarized in Table 6, with associated priority assessments based on their impact on commercial viability and policy decision-making.

Table 6. Identified Research Gaps in Rural Open RAN Deployment Literature

#	Research Gap	Current State	Recommended Approach	Priority / Impact
1	Standardized TCO methodology for rural Open RAN	Fragmented cost metrics; vendor-specific assumptions; no peer-reviewed TCO benchmark	Define unified CAPEX/OPEX/SROI KPI framework; longitudinal multi-site study	Critical – enables policy and investment decisions
2	Long-term multi-vendor field studies	Most evidence is simulation, prototype, or single-vendor [1, 9]	Peer-reviewed 3–5 year field deployment studies with availability, OPEX, and lifecycle data	Critical – underpins commercial viability
3	Standardized KPI sets for rural O-RAN pilots	Heterogeneous metrics impede cross-study comparison [3]	O-RAN Alliance / GSMA joint rural pilot KPI standard	High – enables evidence-based regulation
4	Security and SLA enforcement in neutral-host multi-tenant O-RAN	Qualitative discussion only; no formal models or testbed results	Formal SLA frameworks; end-to-end zero-trust security testbeds	High – prerequisite for commercial neutral-host models
5	NTN/LEO integration with O-RAN functional splits	Handover delay modelled [12]; no end-to-end open-source testbed	LEO-integrated O-RAN living lab with split option evaluation	High – critical for deep rural/maritime coverage
6	Energy storage and hybrid power optimization models	Renewable feasibility shown [2, 17]; no multi-site optimization with battery aging	Stochastic energy management with RIC integration and battery lifecycle model	Medium-High
7	Socioeconomic impact tied to technical design choices	No quantitative linkage between O-RAN strategy and community outcomes	Longitudinal socioeconomic KPI collection alongside technical KPIs in rural pilots	Medium – required for public funding justification
8	AI/ML xApp generalization across multi-vendor rural deployments	xApps validated on single-vendor testbeds only	Cross-vendor xApp portability standards and rural-specific ML training datasets	Medium – essential for scalable intelligence

Priority assessment: Critical = fundamental barrier to commercial deployment; High = significant evidence gap affecting policy; Medium = important for long-term scalability.

Of the eight gaps identified, the absence of standardized TCO frameworks and long-term multi-vendor field studies are assessed as most critical. Without standardized, comparable cost evidence, rational investment decisions by MNOs, development agencies, and governments cannot be made on the basis of published literature. The field evidence that does exist (pilot deployments in Ghana [8], highway corridor measurements in Finland [19], commercial vRAN in the USA [15]) is not directly comparable due to inconsistent metric definitions, disclosure standards, and deployment contexts.

The integration of AI/ML-driven xApps across multi-vendor rural deployments represents a frontier research area with significant practical implications. Current xApp validation is confined to single-vendor testbeds or simulation environments [9, 16]. The generalization of ML-trained models across diverse hardware and software stacks — particularly under the constrained and variable conditions of rural environments — has not been systematically investigated.

NTN-O-RAN integration for rural and remote coverage is an area of rapidly evolving technical work, driven by the commercial availability of LEO constellation services (Starlink, OneWeb, Amazon Kuiper) and 3GPP standardization of NR-NTN in Release 17 and beyond. The theoretical analysis of Seeram et al. [12] identifies the handover-processing trade-off but does not provide an end-to-end open-source testbed for experimental validation of LEO-integrated Open RAN functional splits — a gap of considerable practical importance.

11. LIMITATIONS OF THE REVIEW AND EVIDENCE BASE

The review has several limitations that should be considered when interpreting its findings. First, many quantitative Open RAN claims for rural environments are still derived from simulations, analytical models, vendor white papers, standards use cases, or short-term pilot reports rather than independently audited, multi-year, multi-vendor field deployments. Second, the grey-literature component is necessary because rural Open RAN deployments are still emerging, but it introduces potential reporting bias because vendors and operators may selectively disclose favorable performance indicators. Third, the review could not normalize all cost claims into a single TCO baseline because sources differ in geography, spectrum bands, energy assumptions, discount rates, traffic load, and sharing models. Fourth, pilot cases such as the Ghana TVWS/NuRAN deployment demonstrate feasibility but do not provide sufficient public evidence on long-term OPEX, site availability, subscriber churn, traffic growth, or commercial sustainability. These limitations reinforce the need for standardized KPI reporting and longitudinal field studies.

12. CONCLUSION

This systematic literature review has synthesized evidence from 27 peer-reviewed studies and authoritative industry sources to characterize the landscape of Open RAN deployment strategies for rural and remote areas, evaluate quantitative performance evidence, and identify open research gaps. The review demonstrates that Open RAN provides a flexible architectural foundation for rural connectivity, but that its commercial viability depends critically on tailoring deployments to the specific topology, backhaul, energy, and regulatory constraints of the deployment context. The strength of evidence remains uneven: architecture and optimization claims are supported by a mixture of peer-reviewed studies, simulations, standards work, vendor reports, and pilots, while long-term commercial sustainability remains insufficiently demonstrated in publicly available rural field data.

Six interdependent strategy dimensions are identified and synthesized: topology-aware functional splitting with SMO/RIC placement at regional edge nodes; hybrid backhaul architectures combining fiber, microwave, satellite (particularly LEO), and TVWS; infrastructure and spectrum sharing models (neutral-host MOCN/MORAN and OneRAN pooling); RIC-driven energy automation (ORTP-style xApps with ~20% dynamic power reduction and SMO automation with ~10% OPEX reduction over five years); renewable energy integration with commercially viable financing structures; and TCO-based viability and subsidy modeling.

Eight research gaps are identified, of which the absence of standardized TCO frameworks and long-term multi-vendor field studies are most critical. Addressing these gaps requires coordinated effort from the O-RAN Alliance, GSMA, academic research institutions, and development finance organizations to establish common KPI frameworks, mandate transparent pilot disclosures, and fund comprehensive living laboratory deployments in representative rural and remote environments.

Open RAN is not a universal solution to rural connectivity challenges, but the cumulative evidence of this review demonstrates that, when deployed with topology-aware architectural design, hybrid backhaul, shared infrastructure models, and renewable energy systems, it represents the most promising path toward commercially sustainable rural mobile coverage at the scale required to achieve universal connectivity by 2030.

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PRISMA-guided review of 27 studies and reports (2016–2026)

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