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The Agrarian Matrix: A Conceptual Agriculture–Energy–Telecommunications Framework for Rural Infrastructure in Nigeria

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ABSTRACT

Nigeria's rural economy is constrained at the same time by unreliable electricity, high post-harvest losses and uneven telecommunications coverage, yet these problems are planned and financed in separate sectoral programmes. This article is a desk-based conceptual study; it is not a deployed or experimentally validated system. It proposes the "Agrarian Matrix", a framework in which agricultural production, embedded electronic systems and telecommunications infrastructure are designed together around shared solar-powered rural infrastructure. Using a purposive, tiered compilation of secondary evidence from regulatory, multilateral, peer-reviewed, programme and media sources, the study reports that rural electricity access was about 33% in 2023 against about 89% in urban areas (access, not reliability); that the grid has about 13,000 MW of installed capacity but only 5,151 MW was available for dispatch in December 2025, with delivered energy lower still; and that reported post-harvest losses range from 5–20% for grains to 50–60% for tubers, fruits and vegetables, with a media-reported valuation of about ₦3.5 trillion a year that could not be verified against primary data. The framework comprises a five-layer node architecture, illustrative sizing assumptions, three testable hypotheses on the benefits of co-engineering, and a phased roadmap. Components of the framework have been piloted separately in Nigeria, but no integrated field validation exists, so the benefits attributed to co-engineering remain hypotheses. The contribution is an organising framework and research agenda; scenario-based techno-economic analysis and paired pilot comparisons are the priority next steps.

INTRODUCTION

Nigeria is Africa's most populous country, with more than 230 million people, and it holds substantial rural development assets: about 70.8 million hectares of arable land, of which only about 44% is cultivated (Punch Editorial Board, 2024); strong solar resources suited to distributed power generation; and one of the continent's largest mobile markets, with 175.3 million active telephony subscriptions by December 2025 (Vanguard, 2025b). Yet chronic power shortages, heavy post-harvest food losses and a rural digital divide persist. These problems are usually planned, financed and regulated as three separate sectoral concerns, even though their value chains overlap in the same rural geography.

The electricity sector illustrates the scale of the gap, but installed, available and delivered capacity must be distinguished. Installed grid-connected capacity exceeds 13,000 megawatts (MW), yet data from the Nigerian Electricity Regulatory Commission (NERC), reported by Guardian Nigeria (2026b), show only 5,151 MW, a plant availability factor of 38%, available for dispatch in December 2025. Available capacity is not delivered energy: the transmission network has a theoretical wheeling capacity of 7,500 MW but is reported to move closer to 5,300 MW, and transmission and distribution losses are reported at up to 40%, against a global benchmark of 8–12% (Technext24, 2026). Total or near-total grid collapses have recurred, including events

reported in late December 2025 and on 23 January 2026 (Guardian Nigeria, 2025, 2026a; Technext24, 2026).

Access is also uneven. World Bank data show electricity access of 61.2% of the population in 2023, with 32.9% in rural areas against about 89% in urban areas (International Energy Agency et al., 2025; World Bank, 2025). These indicators measure access to any electricity source, including off-grid solar, and do not describe reliability; other sources report that fewer than 30% of rural residents have reliable power (Climate Scorecard, 2025), which is a different indicator and is not equated with the World Bank access rate here.

Agriculture remains central to the economy. It contributed 23.53% of nominal gross domestic product (GDP) in 2025, and 25.67% in the seasonally high fourth quarter (National Bureau of Statistics [NBS], 2026), and it employs roughly one-third of workers (about 33.5% in 2025 on International Labour Organization modelled estimates; Statista, 2026). Reported post-harvest losses differ sharply by commodity: the Federal Ministry of Agriculture and Food Security, as cited by BusinessDay (2024), estimates 5–20% for grains, about 20% for fish and 50–60% for tubers, fruits and vegetables. Monetary valuations are less secure: BusinessDay (2024) cites about ₦3.5 trillion a year and Punch (2025) reports about US$10 billion a year, and neither is traced here to a primary methodology. Much of the loss is associated with missing cold-storage, drying and processing infrastructure that depends on reliable electricity (Punch, 2025).

In telecommunications, the Nigerian Communications Commission (NCC) data reported by Nairametrics (2025) put broadband penetration at 50.58% in November 2025, still short of the 70% target of the National Broadband Plan 2020–2025 (TechCabal, 2025). Rural backhaul gaps and fibre cuts, estimated at 30–43 a day, continue to disrupt service (TechCabal, 2025).

The usual policy response treats these as three separate crises: power sector reform and grid expansion under one ministry, agricultural input subsidies and storage programmes under another, and telecom licensing and broadband plans under a third regulator. Government programmes, including the Rural Electrification Agency's (REA) Nigeria Electrification Project (NEP), the national post-harvest loss reduction targets and the National Broadband Plan 2020–2025, have each fallen short of their stated targets, leaving rural communities to absorb compounding deficits in power, food-system efficiency and connectivity (BusinessDay, 2024; TechCabal, 2025). The problem addressed here is the absence of an integrated engineering and policy framework that treats agricultural productivity, electronic automation and telecommunications connectivity as parts of a single infrastructure investment. This article argues that the separation is a plausible contributing cause of underperformance, because the most promising fixes for each problem are technically and economically intertwined. This is a proposition to be tested, not a demonstrated result. A solar mini-grid that only powers household lighting has a thin revenue base and a real risk of financial failure. One that also powers irrigation pumps, cold-storage units and milling equipment, what the sector calls "productive use" loads, generates the daytime, commercially viable demand that can make rural electrification bankable (RMI, 2023; Vanguard, 2025a). In the same way, an agricultural extension or market-information service works better when it can send real-time data over a mobile network riding on the same power infrastructure that runs the cold-storage hub. The Agrarian Matrix concept treats this interdependency as something to design for deliberately.

Existing literature offers partial integrations of these domains (compared in Table 1, Section 2.5): energy–water–food nexus models, agrivoltaics, productive-use mini-grids, digital agriculture and mobile-phone studies. Within the sources reviewed, none treats telecommunications as a co-designed infrastructure layer financed together with energy and agricultural assets. The study matters because it shifts the unit of analysis from individual sectors to the rural socio-technical system in which they converge. For policymakers, it suggests co-locating investment, for instance by requiring that rural electrification concessions include agro-processing loads and last-mile telecom backhaul. For engineers, it offers a reference architecture for solar-powered, IoT-enabled agricultural nodes that can be adapted across agro-ecological zones. For researchers, it brings together three literatures, on energy access, post-harvest technology and rural telecommunications, that are rarely studied side by side.

The aim of this study is to develop and critically present a conceptual framework, the Agrarian Matrix, for co-engineering agriculture, embedded electronics and telecommunications around shared solar-powered rural infrastructure in Nigeria, and to specify the evidence, assumptions and pilot-scale tests needed to validate it. To this end, the study compiles and qualifies secondary evidence on the three deficits, proposes a node-level architecture with illustrative sizing assumptions, formulates testable hypotheses on the benefits of co-engineering, and outlines a phased roadmap and policy recommendations.

Literature Review

The literature behind this article spans three fields that are usually kept apart — energy access and rural electrification, post-harvest agricultural technology, and rural telecommunications — plus a newer body of work on productive use of renewable energy and agricultural

Internet of Things (IoT) systems. This section works through each in turn before pulling out the gap the Agrarian Matrix framework is meant to fill.

Electricity Access and the Nigerian Power Sector

Nigeria's power sector has undergone extensive reform since the Electric Power Sector Reform Act of 2005 and the 2013 privatization of generation and distribution assets. Generation capacity utilization has stayed stubbornly low despite all of that. Vanguard (2026) reports that available generation capacity actually fell by 15% between 2020 and 2025, from 7,792.51 MW to 6,773.10 MW, even as installed capacity nominally grew to roughly 13,625 MW. This figure differs from the 5,151 MW reported as available for dispatch in December 2025 (Guardian Nigeria, 2026b) because the two refer to different dates and measures; they are reported separately in this article and are not combined. Baruwa (2026), in an opinion contribution, attributes the persistent gap between installed and delivered capacity mainly to transmission bottlenecks, noting average daily demand of around 13,000 MW, suppressed latent demand closer to 20,000 MW, and a transmission network that can reliably move only about 5,300 MW. Because this is opinion rather than regulatory data, it is used only to support interpretation. That diagnosis matters here because it suggests grid extension alone won't solve rural energy poverty within any reasonable timeframe, which strengthens the case for decentralized generation.

A useful reference point comes from the mid-2010s. Around 2015, Nigeria's electricity access rate stood at nearly 60%, according to World Bank figures, split between 86% in urban areas and 41% in rural areas, while access to non-solid cooking fuels reached only about 4% (SEforALL Africa Hub, n.d.). As an ECOWAS member, Nigeria joined the region's Sustainable Energy for All (SEforALL) Country Action process, adopting an Action Agenda Alongside Renewable Energy and Energy Efficiency Action Plans. Under that framework the country set targets of 75% electricity access by 2020 (90% urban, 60% rural) and 90% by 2030, alongside plans to grow installed generation capacity from 7,500 MW in 2015 to 115,000 MW by 2030 and to raise energy efficiency by at least 20% by 2020 and 50% by 2030 (SEforALL Africa Hub, n.d.). Measured against the access and capacity figures reported elsewhere in this article, most of these targets remain a long way from being met.

Decentralized and renewable alternatives have picked up policy and donor attention as a result. The Rural Electrification Agency's Nigeria Electrification Project (NEP), backed by a $350 million World Bank loan, supported the establishment of 125 mini-grids and the sale of over a million solar home systems, enabling more than 5.5 million Nigerians to gain access to electricity between 2018 and 2024 (World Bank, 2024). Its successor, the Distributed Access through Renewable Energy Scale-up (DARES) project, backed by $750 million in World Bank financing, targets electricity access for 17.5 million more Nigerians through mini-grids and standalone solar systems (Vanguard, 2025a). Energypedia (2025) reports more than 150 solar mini-grids operating under REA/NEP by 2024, with combined capacity near 10 MW, alongside a growing cluster of Nigerian clean-tech start-ups offering smart meters and AI/IoT-based remote monitoring.

A parallel academic literature has looked at how to optimize these systems technically. Agbo et al. (2025), applying the MicroGridsPy modelling framework to a rural farming community in northeastern Nigeria, found that a hybrid solar photovoltaic, battery storage, and diesel back-up configuration achieved renewable energy penetration of 94.7% with generator contribution below 6%, identifying this as the most cost-effective option once capacity expansion is staged over time. This is a single-site modelling result and should not be generalized to other zones. Separately, the engineering literature on IoT in agriculture documents benefits and challenges for sensing, automation and data analytics (Elijah et al., 2018), but this review located little field-based evidence that combines IoT-enabled solar mini-grids with agricultural loads in Nigerian farming communities, and field implementation and economic analysis remain priorities for future work.

Post-Harvest Losses and Agricultural Value Chains

The post-harvest loss literature keeps pointing to storage, processing, and transportation — not on-farm production — as the most loss-intensive stages of Nigeria's agricultural value chain. Abulude and Wahlen's (2024) systematic review locates the critical point of food loss in the gap between production and the postharvest stages of processing, storage, and distribution, noting that fruits, vegetables, and root and tuber crops suffer the highest losses because they move through informal markets without adequate packaging, cooling, or environmental control. A meta-analysis by Ngoma et al. (2024) found that hermetic storage bags substantially outperform conventional bags for grain — cutting seed-viability loss, insect infestation, physical damage, and weight loss several-fold — which points to a low-cost, power-independent intervention worth pairing with the electrified cold-chain solutions discussed later in this article. Empirical work by Lawal et al. (2022) on arable crop farmers in Ogbomoso, Oyo State, and by Ijigbade et al. (2023) on the tomato value chain in southwest Nigeria similarly traces losses to inadequate on-farm storage and the absence of cold-chain infrastructure linking farms to markets (Development Agenda for Western Nigeria Commission [DAWN Commission], 2025).

Nationally, the Federal Ministry of Agriculture and Food Security's estimates of 5–20% for grains, around 20% for fish, and 50–60% for tubers, fruits, and vegetables (BusinessDay, 2024) are broadly consistent with USAID's estimate that roughly half of fresh produce is lost after harvest (Nairametrics, 2024) and with an FAO specialist's estimate of about 50% loss across the food supply chain (Punch Editorial Board, 2024). These are media-reported figures whose definitions (loss at which stage, measured how) are not stated, so they are treated as indicative ranges rather than precise rates.

Policy has tried to respond. Targets reported by the DAWN Commission (2025) include a 30% reduction in post-harvest losses by 2025 under Nigeria's National Agricultural Policy (2021) and a 50% reduction by 2027 under the National Agricultural Technology and Innovation Policy (NATIP) 2022–2027 (Federal Ministry of Agriculture and Rural Development [FMARD], 2022), both aligned with the African Union's Malabo Declaration goal of halving post-harvest losses by 2025. These are relative reductions from an unspecified baseline, not absolute loss-rate thresholds. On the technology side, documented interventions include the Nigerian Stored Products Research Institute's hermetic and dust-based pest-control products, solar-powered cold-storage units deployed by firms such as ColdHubs since 2015, and community-led solar-drying innovations piloted by state agricultural development programmes (Premium Times, 2024).

Telecommunications Infrastructure and Rural Connectivity

Nigeria's telecommunications sector has grown quickly in subscriber terms even as broadband infrastructure lags behind policy targets. NCC data show active telephony subscriptions climbing from 169.3 million in July 2025 to 175.3 million by December 2025, with broadband subscriptions passing 109 million and penetration reaching 50.58% in November 2025 (TechAfrica News, 2025; Vanguard, 2025b; Nairametrics, 2025). That growth still fell short of the National Broadband Plan's 70% target for 2025, and the sector remains held back by real infrastructural vulnerabilities: TechCabal (2025) reports 30 to 43 incidents of fibre-optic cable vandalism a day, on top of high Right-of-Way fees charged by some state governments — both of which push up costs and slow network expansion into underserved areas.

The NCC's 2024 year-end performance report documents the physical infrastructure behind this network, including 39,880 telecommunications towers nationwide, and ongoing efforts — formalized through the 2024 Executive Order on the Designation and Protection of Critical National Information Infrastructure — to curb attacks on towers, fibre cables, and masts (Nigerian Communications Commission [NCC], 2025). For rural and agricultural applications specifically, mobile coverage is the layer that enables SMS-based market price information, mobile money and agricultural finance, remote sensor data transmission, and — increasingly — Low-Power Wide-Area Network (LPWAN) protocols such as LoRa and Narrowband IoT (NB-IoT), which let low-bandwidth, low-power agricultural sensors transmit data over long distances (Mekki et al., 2019).

Productive Use of Energy and the Agriculture-Energy-ICT Nexus

The strand of literature most directly relevant to this article's central argument is the still-small but growing body of work on "productive use of energy" in rural electrification. RMI (formerly Rocky Mountain Institute, 2023), working with mini-grid developers and agricultural equipment companies across nearly 30 partner organizations in Nigeria, found that pairing agricultural processing — cassava grating, maize and rice milling, traditionally powered by diesel — with mini-grid electricity improves rural livelihoods, strengthens the financial case for rural electrification by creating productive daytime load, and lowers electricity prices for everyone on the network. Their accelerator programme tested eleven distinct energy-agriculture business models across roughly 20 pilot sites, ranging from electric two-wheelers supporting farmer extension services to electrified processing equipment (Energizing Agriculture Programme, 2023). Reporting on the REA's 2023 programme data cites 1,668 solar-powered irrigation pumps deployed nationally, covering 24,000 hectares of farmland, alongside 18,300 solar streetlights (Vanguard, 2025a), whereas the REA (2023) itself reported 1,392 pumps in January 2023; the counts were not reconciled and probably reflect different reporting dates.

Even so, RMI (2023) is blunt about a coordination gap: mini-grid developers are largely left to figure out agricultural productive use on their own, with little connection to the agricultural development experts working the same problem in parallel across Nigeria. That observation is probably the clearest statement in the literature of the exact problem the Agrarian Matrix framework is trying to solve — that energy, agriculture, and, by extension, the telecommunications systems connecting both to markets and information, are developing along parallel tracks that barely talk to each other, instead of as one co-engineered system.

Synthesis and Identified Gap

Three things stand out from this review. First, each of the three domains — power, agriculture, and telecommunications — has been studied extensively and sits under active national policy attention, with measurable, government-published targets and statistics. Second, within each domain, the main barrier looks

infrastructural and economic rather than purely technological: transmission bottlenecks choke power delivery despite adequate nominal generation capacity; missing cold-chain and processing infrastructure (itself power-dependent) drives post-harvest losses despite adequate farm-level production; and fibre vandalism, Right-of-Way costs, and uncertain rural revenue hold back telecom expansion despite the technology being available. Third, the productive-use-of-energy literature offers early, encouraging evidence that deliberately co-locating agricultural and energy investment improves outcomes in both domains at once — but this remains the exception rather than the organizing principle of Nigerian rural infrastructure policy, and it hasn't yet been extended systematically to include telecommunications as a third, equally integrated layer.

To test whether an integrated tri-domain framework already exists, Table 1 compares the principal prior strands of work on energy, agriculture and information and communication technology (ICT). Each strand integrates at most two of the three domains as core elements; the closest, productive-use mini-grid programmes, treat connectivity as an incidental feature rather than a co-designed layer. This conclusion is limited to the sources reviewed and should be read as "no integrated framework identified", not as proof of absence. This article addresses the gap by proposing the Agrarian Matrix as an explicit tri-domain co-engineering framework, with an architecture, a compiled evidence base and an implementation roadmap.

Table 1: **Comparison of Prior Energy–Agriculture–ICT Strands of Work and the Agrarian Matrix**

Strand and representative sources	Energy	Agriculture	ICT / telecom	Limitation relative to the Agrarian Matrix
Energy–water–food nexus (Bazilian et al., 2011; Hoff, 2011)	Core	Core	Not addressed	Policy and modelling nexus; no node-level engineering, telecommunications or embedded-electronics layer
Agrivoltaics (Dupraz et al., 2011)	Core	Core	Not addressed	Land-use co-location of PV and crops; no connectivity or post-harvest chain
Productive-use mini-grids (Energy Sector Management Assistance Program [ESMAP], 2019; RMI, 2023; Agbo et al., 2025)	Core	Partial (loads, processing)	Incidental	Connectivity not designed in; coordination gap with agricultural actors noted by RMI (2023)
Digital and IoT agriculture (Aker, 2011; Elijah et al., 2018)	Assumed available	Core	Core	Power supply assumed rather than co-engineered; rural grid deficits not treated
Mobile telephony and agricultural markets (Aker & Mbiti, 2010)	Not addressed	Partial (market information)	Core	Energy and on-farm electronics outside scope
Agrarian Matrix (this study)	Core	Core	Core	Co-engineered as one rural infrastructure unit; conceptual, not yet field-validated

Note. Classification by the authors from the cited sources; "Core" = central design element, "Partial" = addressed in part, "Incidental" or "Assumed" = present but not designed for.

MATERIALS AND METHODS

This research uses a desk-based, conceptual-analytical design. It is a purposive compilation of secondary evidence combined with conceptual systems modelling, not a systematic review: no screening counts are reported because the evidence was selected for relevance and traceability rather than exhaustively. The approach fits where the inquiry stands: The Agrarian Matrix is proposed as a new integrative framework rather than the output of a field experiment, and its empirical grounding comes from compiling, qualifying and cross-checking independently published sources, not from primary data collection.

Evidence Selection and Verification Protocol

Sources were located through keyword searches of Google Scholar and ScienceDirect for peer-reviewed work and of the websites of official bodies (NBS, NCC, NERC, REA, the World Bank and ESMAP), supplemented by searches of Nigerian news archives for regulator statements not otherwise accessible. Representative search strings combined terms such as ("rural electrification" OR "mini-grid") AND Nigeria AND ("productive use" OR agricultur*); ("post-harvest loss*" OR "food loss") AND Nigeria; (IoT OR LoRa OR "NB-IoT") AND agricultur *AND solar; and Nigeria AND broadband AND rural. Items were included if they were Nigeria-specific or directly relevant to the three*

domains, attributable to a named institution or author, dated, and (for statistics) accompanied by a year and recognisable definition. Items were excluded if undated or unattributed, if they merely repeated another outlet's figure without adding information, or if they were opinion pieces offered as data. Source verification and updating of the fast-changing 2025–2026 statistics were completed in October 2026.

Quality appraisal used the four-tier evidence hierarchy in Table 2. For each quantitative indicator the following fields were extracted: value, unit, reference year or period, definition, original source, secondary outlet (if any) and evidence tier. Tier 4 sources were used only where a Tier 1 source could not be accessed, and are labelled "media-reported" in the text and tables.

Table 2: **Evidence Hierarchy Used to Select and Qualify Secondary Sources**

Tier	Source type	Examples in this study	Use in the analysis
1	Official statistical, regulatory and multilateral data	NBS; NCC; NERC (via press reports); World Bank indicators; REA	Preferred for quantitative indicators
2	Peer-reviewed literature	Agbo et al. (2025); Abulude and Wahlen (2024); Ngoma et al. (2024); Aker (2011)	Mechanisms, methods and system-level performance
3	Programme, practitioner and policy documents	RMI (2023); ESMAP (2019); FMARD (2022); DAWN Commission (2025)	Programme scale, policy targets, pilot evidence
4	Journalism and data aggregators	BusinessDay; Vanguard; Guardian Nigeria; Punch; Technext24; Nairametrics; TechCabal; Statista	Only where Tier 1 was inaccessible; flagged "media-reported"; opinion pieces used for interpretation, never as data

Conflicting secondary figures were reconciled by five rules. (1) Primary sources were preferred over secondary reports. (2) Figures were compared only when definitions and reference periods matched; otherwise they are reported separately, for example installed, available and delivered capacity, or electricity access versus reliable access. (3) Where figures differ because they belong to a time series (for instance monthly broadband penetration of 48%, 49.3%, 49.89% and 50.58% reported across 2025), the latest dated value is used and the others are treated as earlier points. (4) Where discrepancies could not be resolved (for instance the ₦3.5 trillion and US$10 billion annual loss valuations, or 1,392 versus 1,668 irrigation pumps), both values are reported and flagged. (5) Statistics subject to rebasing or revision, such as GDP series, are cited with their release date.

Conceptual Framework Development

The Agrarian Matrix framework grew out of systems-thinking analysis of how the three domains depend on each other technically and economically, following an approach similar to socio-technical systems mapping. The method moved in three steps. First, the core technical components of each domain were identified: production, storage, processing, and market access for agriculture; sensing, control, actuation, and automation for electronics; connectivity, data transmission, and information platforms for telecommunications. Second, points of functional dependency between domains were mapped — for example, how cold storage (agriculture) depends on continuous electricity (electronics/power), and how remote monitoring (electronics) depends on network connectivity (telecommunications). Third, these dependencies were pulled together into a single conceptual diagram (Figure 1) and an illustrative system architecture (Figure 2), which together form the technical backbone of the framework and are laid out in Section 4.

Scope and Limitations of the Method

Because this is a conceptual and policy-analytical article rather than a field trial, it doesn't report new primary measurements — for example, the financial rate of return on a specific deployed system. Instead, it relies on compiled secondary evidence, most importantly the RMI (2023) productive-use accelerator findings and the REA's programme statistics, to show that pieces of the proposed framework have already been piloted, separately, in Nigeria. These pilots report programme outcomes; they do not test the integrated framework. This article's contribution is to bring that scattered evidence together into one architecture and to identify the institutional and financing steps needed to test and scale it. Section 8 revisits these limitations.

The Agrarian Matrix: Conceptual Framework and System Architecture

Defining the Agrarian Matrix

For the purposes of this article, the Agrarian Matrix is a co-engineering framework in which agricultural production systems, embedded electronic control and sensing systems, and telecommunications connectivity infrastructure are planned, financed, and deployed as a

single integrated rural infrastructure unit, with shared power generation as the connective substrate. The word "matrix" is deliberate: the three domains don't interact along one linear chain (energy → agriculture → market, say) but form a lattice of mutually reinforcing relationships, where progress in any one domain is expected to raise the value and viability of the other two. Figure 1 shows this relationship schematically. Agriculture, electronics, and telecommunications sit as three co-equal domains arranged around a central co-engineering core, with two-way links both to the core and to each other. The outer triangle of domain-to-domain links represents direct technical interfaces — an agricultural cold-storage unit (agriculture) is itself an electronic load that needs power-electronic control (electronics) and may report its internal temperature over a cellular network (telecommunications) — while the central core stands for the deliberate engineering and institutional work of co-locating and co-financing these interfaces, rather than leaving them to happen by chance.

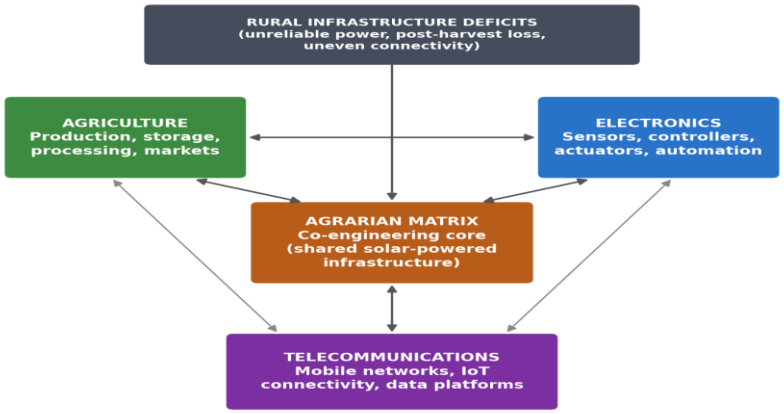


Figure 1. Conceptual framework of the Agrarian Matrix: tri-domain co-engineering of agriculture, electronics, and telecommunications around a shared infrastructure core. Source: Author's construction, informed by RMI (2023) and Energypedia (2025). The figure was redrawn so that the top box names the deficits addressed rather than implying demonstrated mitigation.

System Architecture

Figure 2 turns the conceptual framework into an illustrative technical architecture for a single rural node — say, a village-level mini-grid serving a cluster of farms, a produce aggregation point, and the surrounding households. The architecture has five layers. It is a design concept, not an engineering validation; Section 4.3 states the assumptions needed to make it testable.

Energy Generation and Storage Layer

At the base sits a hybrid energy system combining solar photovoltaic (PV) generation, battery energy storage (BESS), and, where needed, a diesel or biogas back-up generator. This mirrors the optimization findings of recent Nigerian mini-grid modelling research, which identified hybrid solar-battery-generator systems as the most cost-effective configuration for a rural Nigerian site, achieving renewable energy penetration above 94% with generator contribution below 6% of total supply (Agbo et al., 2025). A dedicated power management and hybrid control unit — a charge controller and inverter — governs switching between these sources and handles the direct-current to alternating-current conversion that downstream loads need.

Agro-Electronic Load Layer

The power management layer feeds three parallel subsystems. The first is the agro-electronic sensor and actuator layer: soil-moisture and weather sensors, solar-powered irrigation pumps (of the type already deployed by the REA; Vanguard, 2025a), and cold-storage refrigeration units modelled on the solar-powered ColdHubs design already running in Nigerian markets (Premium Times, 2024). This is where the framework most directly targets the post-harvest loss problem covered in Section 2.2, since reliable, continuous power is a binding constraint on cold-chain viability.

Embedded Control Layer

The second subsystem is an embedded microcontroller node handling local data logging, automated switching (triggering irrigation when soil-moisture sensors cross a threshold, or alerting when cold-storage temperature drifts out of range), and edge processing that trims the volume of raw data needing transmission over the network layer. This layer maps to the "electronics" domain in Figure 1 and is the technical bridge between the physical agricultural assets and the digital telecommunications layer.

Connectivity Layer

The third subsystem is an IoT/cellular transceiver module, which can use conventional GSM/4G-LTE connectivity where mobile coverage is adequate, or Low-Power Wide-Area Network protocols such as LoRa or Narrowband IoT (NB-IoT) in areas with weaker cellular signal but where a LoRa gateway can sit alongside the mini-grid's own infrastructure. This module uplink to the mobile network backbone — the towers, fibre backhaul, and licensed mobile network operator infrastructure described in Section 2.3 — which connects in turn to a cloud or edge analytics platform providing a farm management dashboard and, importantly, SMS or Unstructured Supplementary Service Data (USSD) alerts that don't need a smartphone or a continuous data connection. That design choice matters given Nigeria's broadband penetration of just over 50% (Nairametrics, 2025).

End-User and Market Layer

The architecture ends with three end-user categories: farmers, who get irrigation and storage alerts and basic productivity data; extension agents and aggregators, who use the same platform to coordinate technical support and produce collection; and market and finance platforms, through which farmers can reach price information, buyers, and — where integrated with mobile money — credit and savings products. This end-user layer is what is expected to turn the technical architecture into productive economic activity, which, per the RMI (2023) findings discussed in Section 2.4, is what makes the underlying mini-grid investment financially sustainable in the first place.

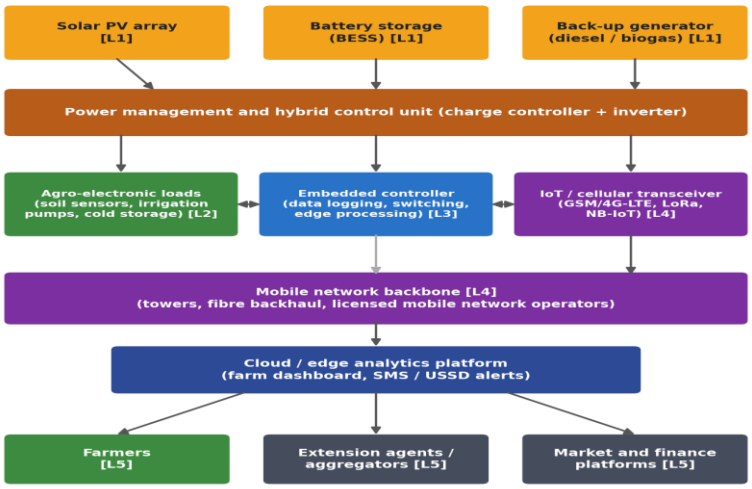


Figure 2. System architecture of a solar-powered agro-electronic-telematic node, showing the flow from energy generation (L1) through agro-electronic loads (L2), embedded control (L3) and connectivity (L4) to end users (L5). Source: Author's construction. The figure was redrawn so that all layers are fully displayed and labelled consistently with Section 4.2.

Illustrative Node Specification, Energy Balance and Validation Needs

Figures 1 and 2 are illustrative and are not engineering validation. To make the architecture testable, Table 3 gives a representative daily energy balance for one hypothetical village node (about 100 households, an irrigation cluster, one cold room, one mill and a connectivity module), and Table 4 sets out design assumptions, constraints and the validation each still requires. All values are the authors' planning assumptions chosen to be typical of small rural nodes; they are not measurements from a deployed system and must be replaced by site data in the scenario-based techno-economic analysis proposed in Section 8.

Table 3: **Illustrative Daily Energy Balance for a Representative Agrarian Matrix Node (Assumed Values)**

Load	Rating or basis	Operating assumption	Daily energy (kWh)	Day (kWh)	Night (kWh)
Irrigation pump	2.2 kW	5 h/day, daytime	11.0	11.0	0.0
Milling / processing	7.5 kW	3 h/day, daytime	22.5	22.5	0.0
Cold room	3.0 kW compressor	5 h full-load equivalent; 60%	15.0	9.0	6.0

		day			
Sensors, controller, gateway	0.15 kW	24 h continuous	3.6	1.8	1.8
Connectivity (LoRa gateway, backhaul radio)	0.5 kW	24 h continuous	12.0	6.0	6.0
Households (100)	0.5 kWh per household per day	Evening-weighted; 20% day	50.0	10.0	40.0
Total			**114.1**	**60.3**	**53.8**

Note. Authors' planning assumptions; peak coincident load is about 20 kW. Productive-use loads (pump and mill) account for about 56% of daytime energy (33.5 of 60.3 kWh).

Under the further assumptions of 5.0 peak sun hours per day, a PV performance ratio of 0.75, a lithium iron phosphate battery operated to 80% depth of discharge and a 90% round-trip efficiency, the night-time energy of 53.8 kWh implies a nominal battery capacity of about 75 kWh (53.8 ÷ (0.8 × 0.9)). The PV array must supply the daytime load plus battery charging, about 120 kWh per day (60.3 + 53.8 ÷ 0.9), which implies an array of about 32 kWp (120.1 ÷ (5.0 × 0.75)). A 25 kVA hybrid inverter and a 10–15 kVA back-up generator for extended cloudy periods would be consistent with the 20 kW peak; the generator is not sized here.

Table 4: **Illustrative Design Assumptions, Constraints and Validation Needs for the Node**

Design dimension	Illustrative assumption or constraint	Validation still required
Node specification	About 32 kWp PV, 75 kWh battery, 25 kVA hybrid inverter, 10–15 kVA back-up generator (derived from Table 3)	Site irradiance data, load surveys, metered demand
Telecom coverage	LoRa gateway for sensor reporting within a radius of several kilometres; GSM/4G-LTE or NB-IoT where available (Mekki et al., 2019); SMS/USSD fallback where data coverage is weak	Site signal and link-budget surveys with the mobile network operator
Latency and data constraints	Sensor reporting every 15 minutes; alert delivery within 5 minutes; control loops run locally at the edge, not over the wide-area link	Field latency and packet-delivery tests (targets, not measured values)
Reliability	Design target of at least 95% energy availability to critical loads (cold room, controller, gateway) and at least 95% connectivity uptime	Logged outages over a full seasonal cycle
Security	Device authentication; encrypted uplinks (for example LoRaWAN AES-128 or TLS); role-based dashboard access; physical protection against theft and vandalism of PV, batteries and cabling	Security audit and community site-protection arrangements
Costs	Cost categories: PV, battery, inverter, cold room, pump, mill, sensors, gateway, civil works, operation and maintenance, connectivity fees. No cost figures are asserted because site quotations are not available	Levelised cost of electricity, payback and sensitivity to exchange rate and fuel price
Performance indicators	Energy: service hours, daytime load factor, unit cost. Agriculture: post-harvest loss rate, cold-room temperature compliance. Telecom: data delivery ratio, alert latency, uptime. Socio-economic: farm income, participation of women and youth	Baseline and end-line measurement in paired pilots

Hypothesised Benefits of Co-Engineering

The economic case for the Agrarian Matrix rests on three reinforcing effects that may be hard to achieve when the three domains are planned separately. These are stated as hypotheses, not findings. H1 (load factor): mini-grids that include agricultural productive-use loads will show a higher daytime load factor and a lower unit cost of electricity than comparable household-only mini-grids, because processing and irrigation loads draw power in daylight hours, smoothing the demand curve (RMI, 2023). H2 (shared capital recovery): a single power and connectivity node serving cold storage, milling, sensor networks and households will spread fixed costs, such as site preparation, security and maintenance staff, across several revenue streams and lower the combined unit cost relative to three separate facilities. H3 (data-enabled productivity): connectivity-enabled monitoring and market information will reduce

post-harvest loss and raise farm-gate income compared with sites that have equivalent energy infrastructure but no designed-in connectivity.

Existing evidence supports H1 only indirectly, through RMI (2023), and none of the evidence reviewed tests H2 or H3 for an integrated node. Section 8 proposes scenario-based techno-economic analysis and a paired pilot comparison of three arms (separate deployment, energy–agriculture co-location, and the full Agrarian Matrix) to test them.

RESULTS AND DISCUSSION

Compiled Secondary Evidence and Analysis

This section compiles reported observations on the three domains (Tables 5–8 and Figures 3–4) and separates them from the authors' interpretations. Every indicator carries its reference year, definition and original source; where the original release was not accessible, the secondary outlet is named and the figure is marked "media-reported". None of the values was independently measured by the authors.

The Electricity Deficit

Table 5 summarizes the key indicators of Nigeria's electricity access and grid-performance deficit. Reported observations: installed capacity is about 13,625 MW (Vanguard, 2026) and average daily demand is reported at around 13,000 MW (Baruwa, 2026), but only 5,151 MW (38% plant availability) was available for dispatch in December 2025 and the transmission network is reported to move about 5,300 MW. Interpretation by the authors: installed capacity should not be read as sufficient to meet demand, because it ignores availability, dispatchability and variation of demand over time; the binding constraints lie in available generation, transmission and distribution. Likewise, a reported transmission and distribution loss rate of up to 40% describes losses within the delivery chain; it does not by itself show what share of generated power reaches consumers, which depends on the energy actually dispatched and on how technical, commercial and collection losses are defined. If 40% of energy entering the network were lost, about 60%, not less than 40%, would be delivered.

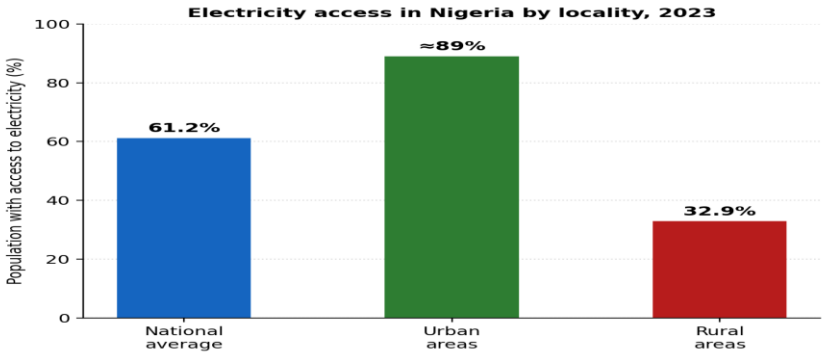


Figure 3. Disparity between urban and rural electricity access rates in Nigeria, 2023 (share of population with access to electricity; access does not measure reliability). Data source: World Bank (2025).

Table 5: **Selected Indicators of Nigeria's Electricity Access and Grid Performance Deficit**

Indicator (definition)	Value	Year or period	Source and evidence type
National electricity access (share of population with access)	61.2%	2023	World Bank (2025); reported dataset
Urban electricity access	About 89%	2023	World Bank (2025); reported dataset
Rural electricity access	32.9%	2023	World Bank (2025); reported dataset
Installed generation capacity	About 13,625 MW	2025–2026 report	Vanguard (2026); media-reported
Available generation capacity (trend)	7,792.51 MW to 6,773.10 MW	2020 to 2025	Vanguard (2026); media-reported
Capacity available for dispatch	5,151 MW (38% plant availability factor)	December 2025	NERC data in Guardian Nigeria (2026b); media-reported
Transmission network theoretical wheeling capacity	7,500 MW	Reported 2026	Technext24 (2026); media-reported

Transmission network practical capacity	About 5,300 MW	Reported 2026	Technext24 (2026); media-reported
Transmission and distribution losses (definition not stated)	Up to 40% (benchmark 8–12%)	Reported 2026	Technext24 (2026); media-reported
Estimated annual economic cost of outages	About US$29 billion (about 10% of projected GDP)	Reported 2026	World Bank estimate as cited by Technext24 (2026); media-reported, not independently verified

Note. Reported observations only; compiled by the authors. "Media-reported" denotes a figure attributed by the outlet to an institution whose original release could not be accessed.

Figure 3 shows the resulting urban-rural gap, which is the piece of the electricity deficit most directly relevant to the Agrarian Matrix framework, given that agricultural production is overwhelmingly a rural activity. A rural access rate of 32.9%, against an urban rate near 89%, means most of Nigeria's farming population lacks access to the electricity needed for irrigation, processing, or storage — precisely the technical functions that post-harvest loss reduction depends on (International Energy Agency et al., 2025; World Bank, 2025).

The Post-Harvest Loss Burden

Table 6 and Figure 4 lay out the reported post-harvest loss data by commodity category. Reported observation: losses stay comparatively moderate for grains, which can be dried and stored with relatively simple infrastructure, and are reported as severe for perishable produce — tubers, fruits, and vegetables — which need cooling or processing within hours or days of harvest. Interpretation by the authors: the commodities with the highest reported loss rates are also those whose loss-reduction technologies (cold storage, drying, processing) are the most power-intensive. This is an observed co-location in the reported figures, not a demonstrated causal relationship.

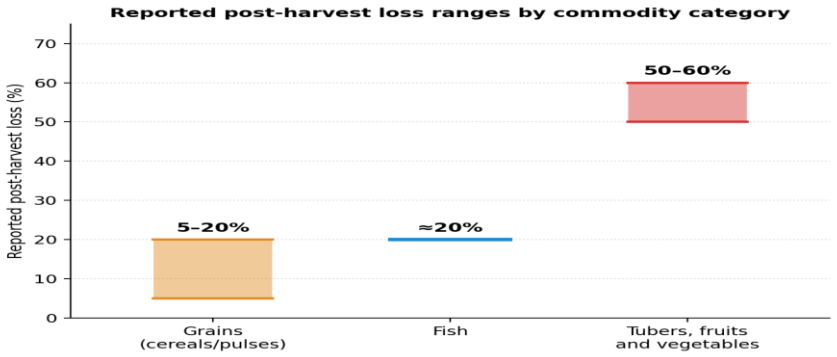


Figure 4. Range of reported post-harvest loss estimates across major commodity categories in Nigeria. Data source: Federal Ministry of Agriculture and Food Security, as cited in BusinessDay (2024). The tubers, fruits and vegetables range was corrected to 50–60% to match the source.

Table 6: **Reported Post-Harvest Loss Rates by Commodity Category in Nigeria**

Commodity category	Reported loss rate	Year	Source and evidence type
Grains (cereals and pulses)	5–20%	2024	Federal Ministry of Agriculture and Food Security, cited in BusinessDay (2024); media-reported
Fish	About 20%	2024	As above
Tubers, fruits, and vegetables	50–60%	2024	As above
Fresh produce (aggregate)	About 50%	2024	USAID, cited in Nairametrics (2024); media-reported
Annual monetary value of losses	About ₦3.5 trillion	2024	BusinessDay (2024); industry estimate, method not stated
Alternative valuation	About US$10 billion a year	2025	Punch (2025); media-reported, method not stated

Note. Reported observations compiled by the authors. Loss definitions (stage, measurement basis) are not stated in the sources; the tomato-specific figure from a blog-hosted analysis was removed for lack of an original source.

BusinessDay (2024) reports an annual loss valuation of about ₦3.5 trillion, more than three times the five-year federal agricultural budget of ₦1.13 trillion cited by the same source. Because the loss figure is an annual, industry-reported estimate of unknown method whereas the budget is a five-year allocation, the comparison is indicative only and does not show that loss reduction would cost less than the loss; the cost of the cold-chain and processing infrastructure was not estimated here (Section 8). The divergence from the US$10 billion valuation in Punch (2025) illustrates how uncertain the monetary figures are.

The Telecommunications Connectivity Gap

Table 7 summarizes telecommunications sector indicators. Nigeria's mobile subscriber growth and its approach toward 50% broadband penetration represent real progress. Even so, the shortfall against the National Broadband Plan's 70% target, combined with daily infrastructure vandalism affecting 30 to 43 fibre-optic cuts and persistent rural coverage gaps, suggests that connectivity — like electricity — remains a binding constraint specifically in the rural and peri-urban areas where agricultural value chains are concentrated (TechCabal, 2025).

Table 7: **Selected Telecommunications Sector Indicators, Nigeria, 2025**

Indicator	Value	Period	Source and evidence type
Active telephony subscriptions	175.3 million	December 2025	NCC data in Vanguard (2025b); media-reported
Broadband penetration	50.58%	November 2025	NCC data in Nairametrics (2025); media-reported (earlier 2025 months: 48%, 49.3%, 49.89%)
Broadband connections (absolute)	About 109.6 million	November 2025	NCC data in Nairametrics (2025); media-reported
National Broadband Plan 2025 target	70%	2020–2025 plan	TechCabal (2025); media-reported
Fibre-optic cable cuts (vandalism)	30–43 per day	December 2025	TechCabal (2025); media-reported
Telecommunications towers nationwide	39,880	2024	NCC (2025); regulator report

Note. Reported observations compiled by the authors. The teledensity and sector GDP-contribution rows in the earlier version were removed because they could not be traced to an original release.

Evidence from Existing Cross-Domain Pilot Programmes

Table 8 lists programmes already running in Nigeria that combine elements of the Agrarian Matrix framework, even where they weren't originally conceived in these terms. These programmes provide indicative evidence on the feasibility of individual components. The REA's mini-grid portfolio, the World Bank-financed NEP and DARES initiatives, and the RMI-coordinated productive-use accelerator together show that (a) solar mini-grids can be deployed at meaningful scale in rural Nigeria, (b) agricultural productive-use loads can be integrated with these mini-grids, and (c) some documented cases report household income increases exceeding 50% in mini-grid-served communities (Energy Transition Africa, 2025); these are programme-reported and are not causally attributed here.

Table 8: **Selected Nigerian Programmes Demonstrating Components of the Agrarian Matrix Model**

Programme	Description and scale (as reported)	Source
Nigeria Electrification Project (NEP)	World Bank-backed ($350m); 125 mini-grids and over 1 million solar home systems; more than 5.5 million beneficiaries (2018–2024)	World Bank, 2024
DARES Programme	World Bank-backed ($750m); targets 17.5 million additional beneficiaries via mini-grids and standalone solar; 8 developers signed by 2025	Vanguard, 2025a
REA/UNDP-GEF Productive-Use Mini-	$5.91m awarded to 18 developers; 23 mini-grids (30–200 kWp); targets post-harvest loss reduction; 70,000	Vanguard, 2025a

Grids	beneficiaries	
Solar-Powered Irrigation Pumps (REA)	1,668 pumps and 24,000 hectares reported by Vanguard (2025a); a capacity of 200 kWp is reported without stating whether it is total or per pump, so it is not interpreted here; REA (2023) separately reported 1,392 pumps in January 2023	Vanguard, 2025a; REA, 2023
RMI Energy-Agriculture Accelerator	About 30 partner organizations; 8 teams; 11 business models tested across about 20 pilot sites linking mini-grids to agro-processing equipment	RMI, 2023; Energizing Agriculture Programme, 2023
ColdHubs Solar Cold-Storage	Solar-enabled walk-in cold rooms and refrigerated transport for market traders and farmers, operating since 2015	Premium Times, 2024

Note. Compiled by the authors from World Bank (2024), Vanguard (2025a), REA (2023), RMI (2023), Energizing Agriculture Programme (2023) and Premium Times (2024). The unverified claim of 5,000 green jobs under NEP was removed.

What none of these programmes has done yet, based on the available evidence, is integrate the third pillar — dedicated telecommunications connectivity for real-time data, remote monitoring, and market linkage — as a designed-in component from project inception, rather than an incidental feature dependent on whatever ambient mobile coverage happens to exist at a given site. That's the specific gap the Agrarian Matrix framework, and the system architecture in Section 4.2, is meant to close. Demonstrated programme outcomes (mini-grid deployment at scale, productive-use pilots, solar cold rooms) must be kept distinct from the projected benefits of the Agrarian Matrix (designed-in connectivity, cost sharing, reduced loss), which remain the hypotheses H1–H3 of Section 4.4.

Discussion

Interpreting the Interdependence

The evidence in Section 5 is consistent with the article's central proposition: Nigeria's power, agricultural, and telecommunications deficits may be three facets of one rural infrastructure deficit rather than three independent problems competing for the same scarce public investment. The clearest illustration is the overlap between the commodities reported to suffer the highest post-harvest losses (tubers, fruits, and vegetables, at 50–60%) and the technical fact that reducing those losses depends on cold storage and processing equipment that can't run without reliable electricity — the resource least available in the rural areas where these commodities are grown. Tackling post-harvest losses through agricultural policy alone, without addressing the underlying rural electricity deficit, may therefore be hard to achieve at scale; this is consistent with, but does not prove, the fact that the post-harvest loss targets (the National Agricultural Policy's 30% target, NATIP's 50% target, and the Malabo Declaration's halving target) have not been reported as met despite repeated policy reaffirmation (DAWN Commission, 2025).

Figure 5 compares the reported baseline loss rates with the loss rates that would be implied if the policy targets were applied to them. The targets are relative reductions from an unspecified baseline year, not absolute loss-rate thresholds, so they cannot be drawn as horizontal lines on a loss-rate axis. The chart therefore shows the midpoint of each reported baseline range (with the range as a whisker, from Table 6) and the illustrative rates implied by a 30% and a 50% relative reduction applied to that midpoint. The implied values are the authors' arithmetic illustrations, not projections.

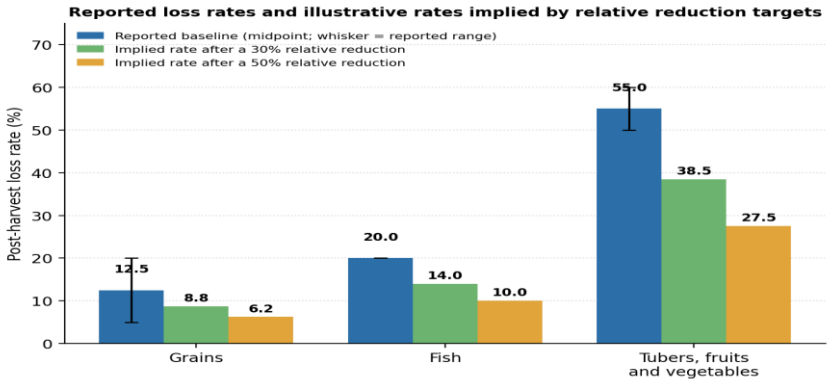


Figure 5. Reported post-harvest loss rates by commodity category (baseline midpoint and range) and illustrative rates implied by 30% and 50% relative reduction targets. Baselines: Federal Ministry of Agriculture and Food Security, as cited in BusinessDay (2024); targets as reported by the DAWN Commission (2025). Implied rates are author-derived illustrations.

The reverse also holds, according to the RMI (2023) accelerator findings: rural electrification investments without a productive-use anchor — mini-grids serving only household lighting — sit on a structurally weaker revenue base than those serving agricultural processing loads. That suggests agricultural productive use isn't just a beneficiary of rural electrification but an active contributor to its financial sustainability, which reframes agriculture from a downstream consumer of power-sector investment into a co-investment partner in it.

The Role of Telecommunications as the Connective Layer

Telecommunications occupies a different position in the Agrarian Matrix than the other two domains. Where agriculture and electronics interact through direct physical and electrical interfaces — a pump draws current, a sensor reports a temperature — telecommunications are the connective layer that turns localized technical performance into system-wide intelligence and market access. That layer's practical reach shouldn't be overstated relative to where deployment actually stands: with national broadband penetration at 50.58% and persistent rural coverage gaps (TechCabal, 2025), any agro-electronic node design has to work in places where continuous broadband connectivity can't be assumed. That's the reasoning, laid out in Section 4.2.4, behind designing the architecture's connectivity layer around SMS/USSD fallback messaging and Low-Power Wide-Area Network protocols rather than assuming smartphone-grade data connectivity at every site.

Distributional and Equity Considerations

Implemented without explicit equity safeguards, the Agrarian Matrix framework risks reproducing the same urban-rural and regional disparities documented in Sections 5.1 and 5.3. Climate Scorecard (2025) notes that government electrification programmes have historically favoured urban centres, where returns on investment are higher and population density lowers the per-connection cost, while northern and conflict-affected regions — which the REA's own 2023 data show received the largest absolute number of mini-grid beneficiaries in the North-Central and North-East zones (Vanguard, 2025a) — face compounding security and logistical constraints. A national rollout of the Agrarian Matrix model should build in explicit targeting criteria favouring high-post-harvest-loss, low-electrification zones, rather than letting site selection default to areas with the lowest implementation cost or the most existing infrastructure, which would just reinforce the disparities already there.

Institutional and Financing Implications

Making the co-engineering vision in Section 4 real requires coordination across at least four regulatory and implementing bodies that don't currently share a common rural infrastructure mandate: the REA and the Nigerian Electricity Regulatory Commission (power), the Federal Ministry of Agriculture and Food Security and its state-level agricultural development programmes (agriculture), and the NCC together with licensed mobile network operators (telecommunications). Nigeria already has a financing precedent for cross-sectoral blended finance, most notably the World Bank-backed NEP and DARES programmes and the REA/UNDP-GEF productive-use mini-grid awards (World Bank, 2024; Vanguard, 2025a) — but these instruments have so far been built around energy access targets with agriculture folded in as a secondary "productive use" category, rather than telecommunications connectivity treated as a co-equal, jointly financed component. A practical first step, taken up in Section 7, would be to formally extend existing productive-use mini-grid financing instruments to require a connectivity component as a condition of disbursement.

Towards Implementation: A Phased Roadmap

Turning the Agrarian Matrix from a conceptual framework into national practice isn't likely to work as a single, simultaneous national rollout, given the scale of Nigeria's geography and how varied its agro-ecological and infrastructural conditions are. Figure 6 proposes a four-phase, eight-year roadmap to sequence the institutional, technical, and financing work involved.

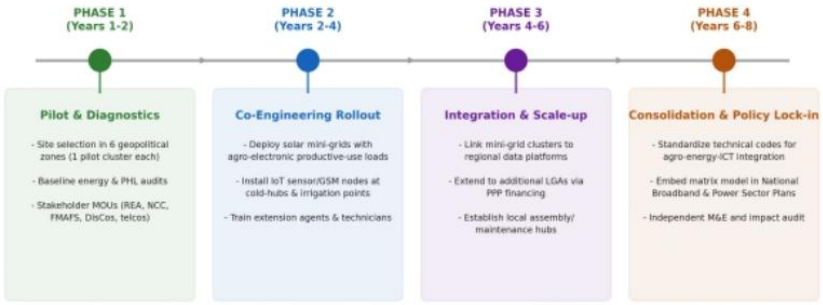


Figure 6. Proposed eight-year phased roadmap for institutionalizing the Agrarian Matrix across Nigeria's six geopolitical zones. Source: Author's construction. The embedded figure number was removed from the image.

Phase 1 (Years 1–2) is diagnostic: selecting one pilot cluster in each of Nigeria's six geopolitical zones, running baseline energy and post-harvest loss audits specific to each site's dominant crops, designing the paired pilot comparison described in Section 4.4, and formalizing memoranda of understanding among the REA, the NCC, the Federal Ministry of Agriculture and Food Security, distribution companies, and at least one mobile network operator per cluster. Phase 2 (Years 2–4) is the co-engineering rollout itself: deploying hybrid solar mini-grids explicitly designed around agricultural productive-use loads, installing IoT sensor and connectivity nodes at cold-storage hubs and irrigation points, and training local extension agents and technicians — addressing the human-capacity side of things that tends to get underweighted relative to hardware in rural technology programmes.

Phase 3 (Years 4–6) shifts toward integration and scale-up: linking individual mini-grid clusters into regional data platforms so aggregated market information and technical support can be shared across sites, extending the model to more local government areas through public-private partnership financing structures modelled on the NEP and DARES precedents, and setting up local equipment assembly and maintenance hubs to cut the foreign-exchange exposure and lead times tied to imported components. Phase 4 (Years 6–8) is about consolidation and policy lock-in: codifying technical standards for agro-energy-ICT integration (minimum connectivity specifications for any REA-financed productive-use mini-grid, for example), formally embedding the co-engineering requirement in the successor instruments to the National Broadband Plan and national power sector strategy documents, and commissioning an independent monitoring and evaluation audit of outcomes against the Phase 1 baseline. Scale-up in Phases 3 and 4 should proceed only if the pilot results support the hypotheses of Section 4.4.

Policy and Institutional Recommendations

The recommendations below follow from the framework and the compiled evidence, and they are conditional on pilot validation. The first priority is financing and mandate design. Existing productive-use mini-grid financing instruments, including those backed by the World Bank and the African Development Bank (AfDB), should be extended to require a connectivity component as a condition of disbursement, so that the telecommunications layer is designed in from project inception rather than left to ambient coverage. A joint power–agriculture–ICT coordination unit involving the Federal Ministry of Power, the Federal Ministry of Agriculture and Food Security and the NCC would address the coordination gap identified by RMI (2023).

The second priority is targeting and service design. Site selection should favour zones with high reported post-harvest loss and low electrification rather than lowest implementation cost, to answer the equity concern in Section 6.3, and advisory services should be built around SMS and USSD because broadband penetration is only about 50%. The third priority is protection and local capacity: vandalism of fibre (30–43 cuts a day) and ageing transmission assets undermine returns on co-engineered investment, which reinforces the 2024 Critical National Information Infrastructure Executive Order, while localising equipment assembly and maintenance would reduce foreign-exchange exposure and improve long-run serviceability. Finally, public funds should support pilot-scale validation before national rollout, so that scale-up is justified by measured results.

Table 9: **Summary of Policy Recommendations for Operationalizing the Agrarian Matrix**

Recommendation	Rationale	Responsible actor(s)

Mandate connectivity in productive-use mini-grid financing	Ensures the telecommunications layer is designed in from project inception rather than left to ambient coverage; closes the gap identified in Section 5.4	REA, NCC, World Bank/AfDB financing instruments
Prioritize high-loss, low-electrification zones in site selection	Directs investment toward areas of greatest need rather than lowest implementation cost, addressing the equity concern raised in Section 6.3	REA, FMAFS, State ADPs
Establish a joint power-agriculture-ICT coordination unit	Addresses the coordination gap explicitly identified by RMI (2023) between mini-grid developers and agricultural development actors	Federal Ministry of Power, FMAFS, NCC
Expand SMS/USSD-based agricultural advisory services	Matches service design to actual broadband penetration (about 50%) rather than assuming smartphone-grade connectivity nationally	NCC, MNOs, agricultural extension services
Strengthen protection of fibre and power infrastructure	Vandalism (30–43 fibre cuts/day) and ageing transmission assets undermine returns on co-engineered investment; reinforces the 2024 Critical National Information Infrastructure Executive Order	TCN, NCC, security agencies
Localize equipment assembly and maintenance	Reduces foreign-exchange exposure and improves long-run serviceability of solar, sensor, and connectivity hardware	Federal Ministry of Industry, private investors
Fund pilot-scale validation before national rollout	Tests hypotheses H1–H3 and replaces illustrative assumptions with measured data	REA, NCC, FMAFS, research institutions

Note. REA = Rural Electrification Agency; NCC = Nigerian Communications Commission; FMAFS = Federal Ministry of Agriculture and Food Security; ADPs = Agricultural Development Programmes; TCN = Transmission Company of Nigeria; MNOs = mobile network operators; AfDB = African Development Bank.

Limitations and Future Research

This article has four main limitations. First, as a conceptual and policy-analytical piece it presents no primary data on the financial or technical performance of an integrated agro-electronic-telecommunications node; the feasibility case rests on programmes, such as the RMI accelerator and the REA's productive-use mini-grids, that piloted pieces of the framework separately rather than as an integrated system with a designed-in connectivity layer. Second, the evidence was selected purposively rather than systematically, and much of it is secondary or media-reported; official Nigerian statistics have in some cases been revised substantially upon rebasing (as with GDP and Consumer Price Index calculations in 2025; NBS, 2026), and several figures could not be checked against primary releases. Readers should treat the point estimates as indicative of order of magnitude and direction. Third, the node specification and sizing in Tables 3 and 4 rest on illustrative assumptions, with no cost estimate. Fourth, the benefits of co-engineering are hypotheses (Section 4.4) and the comparison with separate deployment has not been tested.

Future research should proceed in three steps. A scenario-based techno-economic analysis for representative agro-ecological zones should size the PV–battery–generator system from site irradiance data and load surveys and report levelised cost, payback and sensitivity to exchange rate and fuel price, for separate deployment, energy–agriculture co-location and the full Agrarian Matrix. A paired pilot comparison of those three arms should then measure the indicators in Table 4 against a baseline over at least one full seasonal cycle. Finally, the grid, post-harvest loss and connectivity statistics used here should be re-verified against primary releases from NERC, NBS and NCC as they become available.

CONCLUSION

This article proposed the Agrarian Matrix, a conceptual framework for co-engineering agriculture, embedded electronics and telecommunications around shared solar-powered rural infrastructure in Nigeria. Its contribution is an organising framework, a testable node-level architecture with illustrative sizing assumptions, three hypotheses on the benefits of co-engineering, and a phased roadmap grounded in compiled secondary evidence. That evidence, drawn from regulatory, multilateral, peer-reviewed, programme and media-reported sources, some of which could not be checked against primary releases, indicates that low rural electricity access (about 33% in 2023), limited grid availability (5,151 MW available against about 13,000 MW installed in December 2025) and high reported post-harvest losses (50–60% for perishables) are interrelated constraints, and that components of the

framework have been piloted separately in Nigeria. No integrated field validation exists, however, and the benefits attributed to co-engineering remain hypotheses rather than demonstrated outcomes. The priority is therefore pilot-scale testing, supported by scenario-based techno-economic analysis, before any national rollout; detailed policy recommendations are given in Section 7.

REFERENCES

Abulude, I., & Wahlen, S. (2024). Food loss analysis in Nigeria: A systematic literature review. *Environmental Challenges*, *17*, Article 101027. https://doi.org/10.1016/j.envc.2024.101027

Agbo, C. O., Onori, A., Stevanato, N., Mereu, R., Ogbuka, C. U., Eke, M. N., & Ujah, C. O. (2025). Planning off-grid rural electrification with MicroGridsPy: The case of Dugub, Nigeria. *Energy Strategy Reviews*, *60*, Article 101775. https://doi.org/10.1016/j.esr.2025.101775

Aker, J. C. (2011). Dial "A" for agriculture: A review of information and communication technologies for agricultural extension in developing countries. *Agricultural Economics*, *42*(6), 631–647. https://doi.org/10.1111/j.1574-0862.2011.00545.x

Aker, J. C., & Mbiti, I. M. (2010). Mobile phones and economic development in Africa. *Journal of Economic Perspectives*, *24*(3), 207–232. https://doi.org/10.1257/jep.24.3.207

Baruwa, D. (2026, March 5). National grid collapse: Systemic failure or opportunity gap? [Opinion]. *Premium Times*. https://www.premiumtimesng.com/opinion/860656-national-grid-collapse-systemic-failure-or-opportunity-gap-by-dipo-baruwa.html

Bazilian, M., Rogner, H., Howells, M., Hermann, S., Arent, D., Gielen, D., Steduto, P., Mueller, A., Komor, P., Tol, R. S. J., & Yumkella, K. K. (2011). Considering the energy, water and food nexus: Towards an integrated modelling approach. *Energy Policy*, *39*(12), 7896–7906. https://doi.org/10.1016/j.enpol.2011.09.039

BusinessDay. (2024, September 4). Annual ₦3.5trn post-harvest loss swallows five-year agric budget. https://businessday.ng/agriculture/article/annual-n3-5trn-post-harvest-loss-swallows-five-year-agric-budget/

Climate Scorecard. (2025, June 25). Nearly half of Nigeria's population resides in rural areas, yet fewer than 30% have access to reliable electricity. https://www.climatescorecard.org/2025/06/nearly-half-of-nigerias-population-resides-in-rural-areas-yet-fewer-than-30-have-access-to-reliable-electricity/

Development Agenda for Western Nigeria Commission. (2025). *Reducing post-harvest losses in Southwest Nigeria*. https://dawncommission.org/wp-content/uploads/2025/09/Reducing-Post-Harvest-Losses-in-Southwest-Region.pdf

Dupraz, C., Marrou, H., Talbot, G., Dufour, L., Nogier, A., & Ferard, Y. (2011). Combining solar photovoltaic panels and food crops for optimising land use: Towards new agrivoltaic schemes. *Renewable Energy*, *36*(10), 2725–2732. https://doi.org/10.1016/j.renene.2011.03.005

Elijah, O., Rahman, T. A., Orikumhi, I., Leow, C. Y., & Hindia, M. N. (2018). An overview of Internet of Things (IoT) and data analytics in agriculture: Benefits and challenges. *IEEE Internet of Things Journal*, *5*(5), 3758–3773. https://doi.org/10.1109/JIOT.2018.2844296

Energizing Agriculture Programme. (2023, July 17). *A blueprint for productive use of clean energy: An accelerator in Nigeria generates solutions for linking mini-grids to agricultural equipment in rural communities*. https://energizingagricultureprogramme.org/2023/07/17/blueprint-for-productive-use-of-clean-energy-an-accelerator-in-nigeria-generates-solutions-for-linking-mini-grids-to-agricultural-equipment-in-rural-communities/

Energy Sector Management Assistance Program. (2019). *Mini grids for half a billion people: Market outlook and handbook for decision makers*. World Bank. https://openknowledge.worldbank.org/handle/10986/31926

Energy Transition Africa. (2025, March 28). Solar mini-grids and their impact on rural communities in Africa. https://energytransitionafrica.com/2025/03/28/solar-mini-grids-impact-rural-africa/

Energypedia. (2025, October 27). *Renewable energy landscape and transition pathways in Nigeria: Policy, technology, and local innovations*. https://energypedia.info/wiki/Renewable_Energy_Landscape_and_Transition_Pathways_in_Nigeria:_Policy,_Technology,_and_Local_Innovations

Federal Ministry of Agriculture and Rural Development. (2022). *National agricultural technology and innovation policy (NATIP) 2022–2027*. https://agriculture.gov.ng/wp-content/uploads/2024/06/National-Agricultural-

Technology-and-Innovation-Policy-NATIP-2022-2027.pdf

Guardian Nigeria. (2025, December 30). National grid recovers from 231.50MW power generation drop. https://guardian.ng/news/national-grid-recovers-from-231-50mw-power-generation-drop/

Guardian Nigeria. (2026a, January 23). Again, Nigeria's power grid collapses, causes nationwide blackout. https://guardian.ng/energy/again-nigerias-power-grid-collapses-causes-nationwide-blackout/

Guardian Nigeria. (2026b, January 14). Power generation shrinks by 62% as plants operate below capacity. https://guardian.ng/energy/power-generation-shrinks-by-62-as-plants-operate-below-capacity/

Hoff, H. (2011). *Understanding the nexus: Background paper for the Bonn2011 Conference: The water, energy and food security nexus*. Stockholm Environment Institute. https://www.sei.org/publications/understanding-the-nexus/

Ijigbade, J. O., Agbede, T. M., Johnson, S. B., Olabode, O. G., & Oyeleye, T. A. (2023). Tomato value chain in Southwest Nigeria: An assessment of economic performance. *Scientific Reports in Life Sciences*, *4*(2), 45–57. https://doi.org/10.5281/zenodo.8297992

International Energy Agency, International Renewable Energy Agency, United Nations Statistics Division, World Bank, & World Health Organization. (2025). *Tracking SDG 7: The energy progress report 2025*. World Bank. https://trackingsdg7.esmap.org/

Lawal, O. L., Usman, I. A., Adamu, A. H., Sekinat, M. D., Eromosele, O., & Macuacua, T. L. (2022). Evaluation of factors driving post-harvest losses among arable crop farmers in Ogbomoso, Oyo State, Nigeria. *Journal of Natural Sciences Research*, *13*(6), 1–8.

Mekki, K., Bajic, E., Chaxel, F., & Meyer, F. (2019). A comparative study of LPWAN technologies for large-scale IoT deployment. *ICT Express*, *5*(1), 1–7. https://doi.org/10.1016/j.icte.2017.12.005

Nairametrics. (2024, April 21). Post-harvest losses for fresh produce at almost 50% in Nigeria — USAID. https://nairametrics.com/2024/04/21/post-harvest-losses-for-fresh-produce-at-almost-50-in-nigeria-usaid/

Nairametrics. (2025, December 25). Broadband penetration crosses 50% in November, as Nigeria misses target. https://nairametrics.com/2025/12/25/broadband-penetration-crosses-50-in-november-as-nigeria-misses-target/

National Bureau of Statistics. (2026). *Nigerian gross domestic product report: Q4 and full year 2025* [Statistical release]. https://www.nigerianstat.gov.ng/

Ngoma, T. N., Monjerezi, M., Leslie, J. F., Mvumi, B. M., Harvey, J. J. W., & Matumba, L. (2024). Comparative utility of hermetic and conventional grain storage bags for smallholder farmers: A meta-analysis. *Journal of the Science of Food and Agriculture*, *104*(2), 561–571. https://doi.org/10.1002/jsfa.12934

Nigerian Communications Commission. (2025). *2024 year-end performance report*. https://ncc.gov.ng/sites/default/files/2025-11/2024-Year-End-Performance-Report.pdf

Premium Times. (2024, August 17). Investigation: How Nigeria can resolve its multi trillion naira post-harvest losses (IV). https://www.premiumtimesng.com/agriculture/agric-special-reports-and-investigations/724953-investigation-how-nigeria-can-resolve-its-multi-trillion-naira-post-harvest-losses-iv.html

Punch. (2025, December 1). Nigeria's post-harvest waste: A $10 billion annual loss. https://punchng.com/nigeria-loses-10bn-annually-to-post-harvest-waste/

Punch Editorial Board. (2024, October 9). Unbearable post-harvest losses. *Punch*. https://punchng.com/unbearable-post-harvest-losses/

RMI. (2023, February 9). Electrifying Nigerian agriculture with clean minigrids to improve livelihoods. https://rmi.org/electrifying-nigerian-agriculture-with-clean-minigrids-to-improve-livelihoods/

Rural Electrification Agency. (2023). *FMARD sends letter to REA, commends agency for powering agricultural clusters using renewable energy*. https://rea.gov.ng/fmard-sends-letter-rea-commends-agency-powering-agricultural-clusters-using-renewable-energy

SEforALL Africa Hub. (n.d.). *Nigeria*. Retrieved June 25, 2026, from https://www.se4all-africa.org/seforall-in-africa/country-data/nigeria/

Statista. (2026). *Agricultural sector employment in total employment in Nigeria from 1991 to 2025*. https://www.statista.com/statistics/1288871/agriculture-sector-share-in-employment-in-nigeria/

TechAfrica News. (2025, September 8). NCC report shows 169m active telecom subscriptions as broadband penetration hits 48%. https://techafricanews.com/2025/09/08/ncc-report-shows-169m-active-telecom-subscriptions-as-broadband-penetration-hits-48/

TechCabal. (2025, December 24). Nigeria's internet penetration reaches 50% as 70% target far off. https://techcabal.com/2025/12/24/nigeria-50-percent-internet-penetration-broadband-target/

Technext24. (2026, April 9). Nigeria's power grid keeps collapsing every year. https://technext24.com/2026/04/09/nigerias-power-grid-keeps-collapsing-every-year-can-a-new-software-fix-what-decades-of-neglect-broke/

Vanguard. (2025a, August 26). Nigeria's rural electrification: Renewable energy for remote areas. https://www.vanguardngr.com/2025/08/nigerias-rural-electrification-renewable-energy-for-remote-areas/

Vanguard. (2025b, December 20). Nigeria's telecom subscriptions rise to 175.3m as broadband penetration hits 49.89% — NCC. https://www.vanguardngr.com/2025/12/nigerias-telecom-subscriptions-rise-to-175-3m-as-broadband-penetration-hits-49-89-ncc/

Vanguard. (2026, March 22). Electricity: How Nigeria lost 11,200MW post-privatization. https://www.vanguardngr.com/2026/03/electricity-how-nigeria-lost-11200mw-post-privatization/

World Bank. (2024, June 30). Expanding Nigeria's mini grid market [Feature story]. https://www.worldbank.org/en/news/feature/2025/03/07/expanding-nigeria-s-mini-grid-market

World Bank. (2025). *World Development Indicators: Access to electricity, national, urban and rural (% of population), Nigeria* [Data set]. https://data.worldbank.org/indicator/EG.ELC.ACCS.ZS?locations=NG