
MISSION-AWARE OPTIMISATION OF DEPLOYABLE RENEWABLE ENERGY SYSTEMS FOR CRITICAL RURAL SERVICES IN NIGERIA: A RECONFIGURATION FRAMEWORK

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ABSTRACT

Rural communities in Nigeria often require electricity for different critical services at different times, including agricultural activities, healthcare, and emergency responses. Conventional rural renewable-energy systems are generally fixed-purpose installations, while existing mobile energy-storage research largely focuses on restoration, routing, sizing, and pre-positioning. This paper proposes a Mission-Aware Reconfigurable Energy Hub (MAREH), a deployable photovoltaic–battery energy storage system that retains a common energy backbone while reconfiguring its load priorities according to the active rural mission. The framework integrates photovoltaic (PV) generation, battery storage, supervisory energy management, mission-dependent critical-load prioritization, and deployment-specific electrical safety verification. A two-stage approach is used: the first stage sizes the PV-battery configuration under an ϵ -constraint formulation, minimizing lifecycle cost subject to explicit service-reliability constraints, and the second stage evaluates the sized system, without further optimization, under three missions — agricultural support, healthcare, and emergency response — using scenario-based deterministic simulation. Four scenarios compare fixed-purpose, conventional deployable, and mission-aware configurations using energy not served, critical energy-service coverage (CESC), renewable fraction, battery state of charge, and system cost. Preliminary results indicate the mission-aware configuration achieves approximately 99% or greater critical-service coverage across the three missions using a 7-kWp PV array and 22-kWh battery, an 8.3% reduction in nominal storage capacity and a 4.2% reduction in lifecycle cost relative to the conventional deployable benchmark. This reduction is accompanied by a small decrease in worst-case coverage (approximately 0.65 percentage points), reflecting a deliberate trade-off in which lower-priority loads are curtailed to protect critical services under scarcity, rather than a uniform improvement. The framework demonstrates that reconfigurability can serve as an additional energy-system resource, letting one deployable renewable-energy asset support changing rural priorities without separate dedicated systems at a quantifiable and disclosed reliability cost.

Keywords: mission-aware energy hub; mobile microgrid; PV–BESS; rural electrification; reconfigurable energy system; critical services; Nigeria

1. INTRODUCTION

Reliable electricity remains a major constraint to the delivery of essential services in many rural and underserved communities. The challenge is particularly pronounced where electricity demand is geographically dispersed, conventional grid extension is economically difficult, and critical services

such as healthcare, water supply, agricultural processing, refrigeration, and communications require dependable electricity. Decentralized renewable-energy systems, particularly photovoltaic (PV) and battery energy storage systems (BESS), have consequently become important alternatives for rural electrification and local energy resilience.

In Nigeria, decentralized energy programmes have expanded substantially through mini-grids and standalone solar systems targeted at unserved and underserved communities. However, most of these interventions are conceived as stationary assets, with their generation and storage infrastructure permanently associated with a particular community or facility. This approach is appropriate where the demand location is relatively stable, but it becomes less effective when the highest-priority energy requirement changes spatially or temporally. A rural community may require agricultural support during normal periods, emergency healthcare during a disease outbreak or disaster, and temporary critical services following infrastructure failure. A permanent energy system designed around only one of these functions may consequently remain underutilized during other periods.

The emergence of mobile energy-storage systems provides an alternative pathway. Previous research has investigated mobile energy storage for distribution-system restoration, emergency load recovery, optimal routing, sizing, and pre-positioning. Lei et al. (2019), for example, developed a framework that co-optimized service restoration, repair-crew deployment, and mobile power-source dispatch following distribution-system disruptions. Bose et al. (2022) in the same vein formulated the joint routing of mobile energy storage systems and load restoration in microgrids. Wang et al. (2022) extended the concept toward resilience-driven sizing and pre-positioning of mobile energy-storage systems in decentralized networked microgrids. These studies demonstrate the value of mobility as an energy-system resource, but their principal concern is the movement, positioning, or dispatch of mobile energy resources for network restoration and resilience rather than the reconfiguration of a single deployable energy asset among distinct rural service missions.

A second body of literature concerns renewable-energy-based rural electrification and PV–BESS systems. Such systems can provide electricity where grid extension is difficult or unreliable, while energy storage can improve supply continuity and enable critical loads to operate beyond periods of solar availability. Microgrid control research has also established hierarchical and supervisory control structures capable of coordinating distributed generation, storage, and loads (Bidram & Davoudi, 2012). Energy-storage technologies and their application to microgrids have been extensively reviewed by Faisal et al. (2018).

The challenge addressed in this study is therefore not the invention of mobile PV–BESS hardware. Portable and mobile energy systems already exist in research and practice. Rather, the study asks a different engineering question: can a single deployable PV–BESS energy backbone be configured to serve different rural missions by changing the priority and allocation of its energy services while retaining the same core generation and storage assets?

This question becomes particularly important when the energy hub is deployed as a transportable electrical installation. Relocation introduces additional electrical-safety considerations because the protective arrangement must be established and verified at the new site before energization. International Electrotechnical Commission (IEC 60364-7-717:2026) specifically addresses electrical installations of mobile or transportable units, while IEC 62548-1:2023 (with Amendment 1:2025) provides requirements relevant to PV array design, protection, switching, and earthing (IEC 60364-7-717:2026 - is confirmed as the published third edition of this part, superseding the 2009 second edition, at the time of manuscript preparation)

Accordingly, this paper proposes a Mission-Aware Reconfigurable Energy Hub (MAREH) framework that combines a common PV–BESS energy backbone with mission-dependent load prioritization, deployment-specific electrical safety verification, and rapid service reconfiguration. Three representative missions are considered: agricultural support, healthcare, and emergency response.

The main contribution is the formalization and preliminary quantification of mission-aware reconfiguration as a design and operational layer for a deployable rural energy system. Unlike approaches centered on where mobile energy storage should be located or routed, the proposed framework focuses on what service configuration the same energy asset should adopt when its mission changes.

2. RELATED LITERATURE AND RESEARCH GAP

2.1 Rural Renewable-Energy Systems

PV-based distributed generation combined with battery storage has become an important solution for rural electrification because it can operate independently of conventional electricity networks and can be scaled according to local demand. Hybrid renewable-energy optimization studies have demonstrated the technical and economic feasibility of PV-BESS configurations for isolated communities, including applications relevant to rural Nigeria (Oladeji et al., 2021; Elegeonye et al., 2023) and the wider Sub-Saharan African region (Babayomi et al., 2023)

The principal limitation of a conventional fixed configuration is that system sizing is generally determined by a relatively stable load profile. Consequently, a system optimized for agricultural processing may not be appropriately configured for healthcare or emergency response. Conversely, sizing the system for the highest conceivable demand can increase capital cost and leave generation and storage capacity underutilized during normal operation.

2.2 Mobile Energy Storage and Resilience

Mobile energy storage introduces spatial flexibility into electricity system planning. Lei et al. (2019) demonstrated that mobile power sources can be coordinated with restoration activities to improve distribution-system recovery following disruption. Bose et al. (2022) developed a mixed-integer optimization framework for jointly routing mobile energy-storage systems and restoring curtailed loads. Wang et al. (2022) investigated resilience-driven sizing and pre-positioning of mobile energy storage in networked microgrids, incorporating essential and non-essential loads into the resilience assessment.

These studies establish an important foundation for mobile energy resources but focus primarily on restoration, routing, placement, sizing, and resilience. The proposed framework shifts the focus from the movement of the energy asset to the reconfiguration of its service mission.

2.3 Microgrid Control and Energy Management

Microgrid control architectures have traditionally been organized hierarchically, with lower control layers regulating local voltage, frequency, and power flows and supervisory layers coordinating generation, storage, and loads (Bidram & Davoudi, 2012). This hierarchical concept provides a suitable foundation for mission-aware energy management because a supervisory layer can modify load priorities while the underlying electrical control remains unchanged.

Energy-storage systems are particularly important because they permit energy collected during periods of renewable generation to be allocated according to changing demand requirements (Faisal et al., 2018). In the proposed framework, the BESS is therefore not simply a backup component; it becomes an energy-allocation resource through which the Energy Management System (EMS) can preserve high-priority services during periods of energy scarcity.

2.4 Transportable Electrical Installations and Safety

Physical mobility creates an additional engineering dimension that is often separated from energy optimization. A transportable electrical installation must be safely disconnected, moved, re-established, and verified before operation at the new location. IEC 60364-7-717:2026 specifically applies to electrical installations of mobile and transportable units and includes provisions related to protection against electric shock and additional protection.

For the proposed hub, the electrical safety layer includes protective bonding, earthing, protection against electrical faults, and verification before energization, drawing on the earthing and protective-conductor provisions of IEC 60364-5-54:2011 and the PV-array protection and earthing requirements of IEC 62548-1:2023/AMD1:2025. The safety layer is therefore treated as a deployment gate rather than as an afterthought to the energy-management problem.

2.5 Research Gap

The reviewed literature indicates four related but distinct research streams: rural renewable-energy systems, microgrid energy management, mobile energy storage for resilience, and transportable

electrical-installation safety. However, these streams are rarely integrated around a single rural energy asset that can change its service mission without changing its fundamental generation and storage backbone.

The specific gap addressed in this study is therefore the following:

Existing mobile-energy research largely addresses emergency restoration, mobile-storage routing, sizing, or pre-positioning, while rural renewable-energy studies predominantly consider fixed-purpose systems. Less attention has been given to a single deployable PV–BESS asset whose service configuration is explicitly reconfigured among distinct rural missions — agricultural, healthcare, and emergency — using mission-dependent critical-load priorities while incorporating deployment-specific electrical safety verification.

The contribution is consequently not claimed as novel mobile PV–BESS hardware. Instead, the study proposes a mission-aware engineering framework and preliminary quantitative assessment for converting a deployable energy asset into a flexible provider of different critical rural services.

3. SYSTEM MODELING, OPTIMIZATION, AND SIMULATION METHODS

3.1 Proposed System Architecture

The proposed mission-aware reconfigurable energy hub consists of a PV array, BESS, bidirectional inverter, DC/AC protection, distribution system, supervisory EMS, and mission-dependent loads. The common energy backbone remains physically unchanged while the EMS changes the active service configuration according to the declared mission.

The three missions are:

- M1 — Agricultural mission: agricultural extension and Information and Communication Technology (ICT) services, water pumping, productive loads, lighting, and cold-chain/refrigeration.
- M2 — Healthcare mission: medical equipment, medical refrigeration, water supply, lighting, and communications.
- M3 — Emergency mission: emergency healthcare, water supply, communications, lighting, and other essential community services.

The architecture incorporates three interconnected pathways:

1. Energy pathway: PV → DC protection → BESS/DC bus → inverter → AC distribution → loads.
2. Mission pathway: mission declaration → EMS → load prioritization → dispatch/reconfiguration.
3. Safety pathway: bonding → deployment-specific earthing → protection verification → safe energization.

3.2 PV Generation Model

$$P_{PV} = P_{PV,r} \times \frac{G(t)}{G_r} \times [1 + \gamma \cdot (T_c(t) - T_r)] \times \eta_{sys} \dots \dots \dots (1)$$

Where

- $P_{PV}(t)$: Actual PV power output at time t .
- $P_{PV,r}$: Rated (nominal) PV power under reference conditions.
- $G(t)$: Solar irradiance at time t (W/m^2).
- G_r : Reference irradiance, typically 1000 W/m^2 (Standard Test Conditions).
- γ : Temperature coefficient of power (usually negative, e.g., $-0.004/^\circ\text{C}$).
- $T_c(t)$: PV cell temperature at time t .
- T_r : Reference temperature, usually 25°C .
- η_{sys} : System efficiency factor (accounts for inverter, wiring, and other losses).

3.3 Mission-Dependent Load Model

$$P_{L,m}(t) = \sum_{k=1}^{N_L} x_{m,k}(t) \cdot P_{m,k}(t) \dots \dots \dots (2)$$

Where,

- $P_{L,m}(t)$: Total load power demand for category m at time t .
- N_L : Total number of loads considered in the system.
- $x_{m,k}(t)$: Binary status indicator (0 or 1) showing whether load k in category m is ON or OFF at time t .
- $P_{m,k}(t)$: Power consumption of load k in category m at time t .
- $x_{m,k}(t)$ is the activation state of load group k under mission m .

3.4 Battery Model

During charging:

$$SOC(t+1) = SOC(t) + \eta_c \times P_{ch,t} \times \frac{\Delta t}{E_B} \dots \dots \dots (3)$$

Where,

- $SOC(t)$: Battery state of charge at time t (fraction or %).
- $SOC(t+1)$: Battery state of charge at the next time step.
- η_c : Charging efficiency (accounts for losses, typically 0.9–0.95).
- $P_{ch,t}$: Charging power applied at time t (kW).
- Δt : Time step length (hours).
- E_B : Nominal battery energy capacity (kWh).

During discharging:

$$SOC(t+1) = SOC(t) - P_{dis,t} \times \frac{\Delta t}{(\eta_d \times E_B)} \dots \dots \dots (4)$$

Where,

- $SOC(t)$: State of charge at time t .
- $SOC(t+1)$: State of charge at the next time step.
- $P_{dis,t}$: Discharging power at time t (kW).
- Δt : Time step length (hours).
- η_d : Discharging efficiency (accounts for conversion losses, typically 0.9–0.95).
- E_B : Nominal battery energy capacity (kWh).

with:

$$SOC_{min} \leq SOC(t) \leq SOC_{max} \quad (5)$$

Where,

- $SOC(t)$: State of charge at time t .
- SOC_{min} : Minimum allowable SOC (often 10–20% of capacity, to prevent deep discharge and extend battery life).
- SOC_{max} : Maximum allowable SOC (usually 90–100% of capacity, to avoid overcharging).

$$0 \leq P_{ch,t} \leq P_{ch,max} \quad (6)$$

Where,

- $P_{ch,t}$: Charging power applied at time t (kW).
- $P_{ch,max}$: Maximum allowable charging power (kW), determined by the battery's design and inverter limits.

$$0 \leq P_{dis,t} \leq P_{dis,max} \quad (7)$$

Where,

- $P_{dis,t}$: Discharging power at time t (kW).

- $P_{dis,max}$: Maximum allowable discharging power (kW), set by the battery's design, inverter, and safety limits.

3.5 Energy Balance and Service Adequacy

$$P_{PV,t} + P_{dis,t} = P_{L,m,t} + P_{ch,t} + P_{loss,t} + P_{ENS,t} \quad (8)$$

Where,

- $P_{PV,t}$: PV power generation at time t .
- $P_{dis,t}$: Battery discharging power at time t .
- $P_{L,m,t}$: Load demand for category m at time t .
- $P_{ch,t}$: Battery charging power at time t .
- $P_{loss,t}$: System losses (inverter, wiring, conversion, etc.) at time t .
- $P_{ENS,t}$: Power not supplied (unmet demand) at time t .

Annual Energy not Served:

$$ENS = \sum_{t=1}^N P_{ENS,t} \cdot \Delta t \dots \dots \dots (9)$$

Where,

- ENS: Total energy not supplied (kWh) over the evaluation horizon.
- $P_{ENS,t}$: Power not supplied at time t (kW).
- Δt : Duration of each time step (hours).
- N: Total number of time intervals considered.

Critical Energy-Service Coverage can now be computed has:

$$CESC = \left[1 - \frac{ENS_C}{E_{C,demand}} \right] \times 100 \dots \dots \dots (10)$$

Where,

- CESC: Percentage measure of supply continuity for customer C.
- ENS_C : Energy not supplied to customer C (kWh).
- $E_{C,demand}$: Total energy demand of customer C over the evaluation period (kWh).

3.6 Deployment Safety Model

Relocation is treated as an engineering process rather than simply transportation.

$$\text{Transport} \rightarrow \text{Physical Setup} \rightarrow \text{Bonding/Earthing} \rightarrow \text{Protection Verification} \rightarrow \text{Energization} \quad (11)$$

The safety state is:

$$S_d = 1 \text{ if required safety verification is satisfactory; } 0 \text{ otherwise} \quad (12)$$

Deployment time is therefore stated as follows:

$$T_{\text{deploy}} = T_{\text{transport}} + T_{\text{setup}} + T_{\text{safety}} \quad (13)$$

Where,

- T_{deploy} : Total deployment time.
- $T_{\text{transport}}$: Time required to transport equipment, personnel, or resources to the deployment site.
- T_{setup} : Time required to set up the system, equipment, or infrastructure.
- T_{safety} : Time allocated for safety checks, compliance, and risk mitigation before operation begins.

The model deliberately does not impose one universal earth-resistance value because the acceptance criterion depends on the selected earthing topology, inverter configuration, protective-device characteristics, and applicable installation requirements.

3.7 Two-Stage Optimization and Evaluation

The first stage determines PV and BESS capacities through an explicit optimization. The objective is to have:

$$\min C_{NPC} \quad (14)$$

Where,

- C_{NPC} : Typically stands for *Cost Net Present Cost* (sometimes *Cumulative Net Present Cost*), which represents the total discounted cost of the system over its lifetime.
- $\min C_{NPC}$: The optimization goal is to minimize the net present cost, balancing capital investment, operation, maintenance, replacement, and reliability penalties.

Which is subject to:

$$ENS_C \leq \varepsilon_{ENS} \quad (15)$$

Where,

- ENS_C : Energy not supplied to customer C (kWh), as defined earlier in Eq. (9).
- ε_{ENS} : Maximum allowable energy not supplied (kWh) — a threshold or tolerance level set by the planner.

$$CESC \geq \varepsilon_{CESC} \quad (16)$$

Where,

- $CESC$: Customer Energy Supply Continuity index (Eq. 10), expressed as a percentage of demand met.
- ε_{CESC} : Minimum acceptable continuity threshold (e.g., 95% or 99%), set by planners or regulators.

and the battery, inverter and energy-balance constraints. Net Present Cost is therefore:

$$C_{NPC} = C_{CAP} + C_{REP} + C_{OM} - C_{SALV} \quad (17)$$

Where,

- C_{CAP} : Capital cost — the upfront investment in PV panels, BESS, inverters, and other infrastructure.
- C_{REP} : Replacement cost — expenses for replacing components during the system's lifetime (e.g., batteries after 8–10 years).
- C_{OM} : Operation and maintenance cost — recurring expenses for upkeep, servicing, and monitoring.
- C_{SALV} : Salvage value — the residual value of components at the end of the project lifetime, subtracted since it offsets costs.

An ε -constraint formulation is preferred to an arbitrarily weighted objective because the critical-service requirements can be explicitly imposed as constraints rather than folded into a single scalarized cost with subjectively chosen weights.

The ε -constraint problem in Eqs. (14)–(17) is solved via exhaustive grid-search enumeration of candidate PV capacities (0.5 kWp increments) and BESS capacities (1 kWh increments); each candidate is evaluated against the 8,760-hour deterministic simulation, and the lowest-cost candidate satisfying the ENS and CESC constraints in Eqs. (15)–(16) is selected as the sized configuration reported in Table 1.

The second stage is an evaluation, not a further optimization: the PV–BESS configuration obtained in the first stage is held fixed and simulated under each of the three mission states in turn, so that ENS, CESC and related indicators can be compared across missions for a single sized system.

$$M = \{M1, M2, M3\} \quad (18)$$

Where,

- M : The set of mission states considered in the second-stage evaluation, consistent with the mission definitions in Section 3.1.
- $M1$: Agricultural mission.
- $M2$: Healthcare mission.
- $M3$: Emergency mission

Within each mission m , individual loads are further classified by supply priority using a separate notation, C1/C2/C3 (critical/priority/non-critical), so as not to conflict with the mission labels M1–M3 above: C1 denotes critical loads that must always be supplied (e.g., medical equipment,

emergency communications); C2 denotes priority loads that are important but flexible (e.g., extension services, community facilities); and C3 denotes non-critical loads that can be curtailed during shortages (e.g., non-essential lighting, low-priority appliances). This priority tier $c(k) \in \{C1, C2, C3\}$ is assigned to each load k in Eq. (2) and governs the curtailment order referenced in Sections 4.3 and 4.6.

3.8 Mission Reconfiguration

A mission transition is represented by:

$$M_i \rightarrow M_j \quad (19)$$

Where,

$M_i, M_j \in \{M1, M2, M3\}$: the mission states defined in Section 3.1 (agricultural, healthcare, emergency). M_i is the mission being exited and M_j is the mission being entered.

This mission-level transition is distinct from the within-mission load-priority tiers C1–C3 introduced in Section 3.7, which are unaffected by a mission transition unless the EMS also re-evaluates load-priority assignment under the new mission.

where:

$$T_R = T_{\text{detect}} + T_{\text{decision}} + T_{\text{switch}} \quad (20)$$

Where,

- T_R : Total response time — the duration from the onset of an event to the completion of a corrective action.
- T_{detect} : Time taken to detect the event or fault (e.g., sensor or monitoring delay).
- T_{decision} : Time taken to process information and decide on corrective action (e.g., controller or operator decision-making).
- T_{switch} : Time taken to physically implement the corrective action (e.g., switching circuits, activating backup supply).

When physical relocation is necessary, T_{response} now becomes :

$$T_{\text{response}} = T_{\text{transport}} + T_{\text{setup}} + T_{\text{safety}} + T_{\text{reconfig}} \quad (21)$$

Where,

- T_{response} : Total system response time — the duration from initiation to full operational readiness.
- $T_{\text{transport}}$: Time required to move equipment, personnel, or resources to the deployment site.
- T_{setup} : Time required to assemble and configure the system physically.
- T_{safety} : Time allocated for safety checks, compliance, and risk mitigation.
- T_{reconfig} : Time required to reconfigure or adapt the system to specific conditions (e.g., load adjustments, network re-routing, or controller reprogramming).

3.9 Simulation Scenarios

S1 — Fixed agricultural system: permanently configured for agricultural services.

S2 — Fixed healthcare system: permanently configured for healthcare services.

S3 — Conventional deployable system: physically transportable but operated without the proposed mission-aware load-prioritization strategy.

S4 — Proposed mission-aware system: a common PV–BESS backbone dynamically reconfigured between M1, M2, and M3.

3.10 Performance Indicators

The principal indicators are Net Present Cost (NPC), ENS, CESC, RF, $SOC_{\min}$ and response/reconfiguration time. Renewable fraction is:

$$RF = \left[\frac{E_{PV, \text{supplied}}}{E_{\text{total}, \text{supplied}}} \right] \times 100 \quad (22)$$

Where,

- RF: Renewable fraction (%) — the share of total supplied energy that comes from PV.
- $E_{PV, \text{supplied}}$: Energy supplied by PV generation over the evaluation horizon (kWh).

- $E_{\text{total, supplied}}$: Total energy supplied to loads (kWh), including PV, BESS discharge, and possibly other sources.

4. CASE STUDY, SIMULATION RESULTS AND DISCUSSION

4.1 Case-Study Basis

A representative off-grid rural Nigerian community is considered. The proposed hub operates independently of the utility grid and can be relocated where required.

Three mission load profiles are considered. The preliminary average daily demands are approximately 26.4 kWh/day for agricultural operation, 34.2 kWh/day for healthcare operation and 36.1 kWh/day for emergency operation.

These load figures are planning-level estimates derived from assumed appliance loads and duty cycles rather than site-measured Nigerian data; consequently, the numerical results reported in Sections 4.2–4.4 (including cost and coverage figures presented to one decimal place) should be read as illustrative outputs of this preliminary model rather than validated, deployment-ready estimates.

4.2 Preliminary PV–BESS Configurations

Table 1: Preliminary PV–BESS configurations

Scenario	Configuration	PV (kWp)	BESS (kWh)	Approx. NPC
S1	Fixed agricultural	5.0	16	\$12,400
S2	Fixed healthcare	6.5	23	\$15,900
S3	Conventional deployable	7.0	24	\$16,700
S4	Mission-aware	7.0	22	\$16,000

Planning-level model outputs based on assumed component costs, rounded to the nearest \$100 to reflect their illustrative nature; not current Nigerian market quotations. Actual figures may vary by approximately ± 10 –15% depending on component sourcing and exchange rates.

The preliminary optimization indicates that the mission-aware system requires approximately 7 kWp PV and 22 kWh BESS. Relative to the conventional deployable benchmark, the proposed configuration reduces nominal battery capacity by approximately 8.3%.

4.3 Mission-Level Performance

Table 2: Preliminary mission-level performance of S4

Mission	Annual (kWh)	ENS	CESC (%)	Renewable fraction (%)	Minimum SOC (%)
M1 Agricultural	1,322.2		100.0	68.7	59.2
M2 Healthcare	621.3		100.0	56.2	26.0
M3 Emergency	471.7		99.1	55.0	20.0

The results demonstrate that total ENS is not necessarily equivalent to critical-service failure. The mission-aware controller allows lower-priority loads to be curtailed when available energy becomes constrained while protecting critical services.

4.4 Conventional Versus Mission-Aware Deployment

Table 3: Preliminary comparison between S3 and S4

Indicator	S3 Conventional	S4 Mission-aware	Difference
PV capacity (kWp)	7.0	7.0	0
BESS capacity (kWh)	24	22	−8.3%
Approx. NPC	\$16,700	\$16,000	−4.2%
Minimum CESC (%)	99.75	99.10	−0.65 percentage point
Average renewable fraction (%)	55.3	60.0	+4.7 percentage points
Minimum SOC (%)	20.0	20.0	Same

The comparison indicates that mission-aware reconfiguration reduces nominal battery capacity by approximately 8.3% and lifecycle cost by approximately 4.2% relative to the conventional deployable benchmark. This is not a uniform improvement: it is accompanied by a small reduction in worst-case critical-service coverage, from 99.75% under S3 to 99.10% under S4, a decrease of 0.65 percentage points. This reflects a deliberate design trade-off rather than an unqualified gain — the mission-aware controller achieves its capacity and cost reduction precisely by curtailing non-critical loads when energy becomes scarce, which slightly relaxes the worst-case reliability margin relative to a conventionally sized deployable system. Whether this trade-off is acceptable depends on the tolerance for marginal reductions in critical-service coverage in exchange for lower capital cost and reduced battery capacity and should be stated as an explicit design choice rather than presented as a strictly dominant result.

These percentage differences are point estimates from a single deterministic scenario set using assumed cost and load parameters; they have not yet been tested against alternative cost assumptions or solar-resource years, and a sensitivity analysis is identified as a priority next step (Section 5).

4.5 Deployment and Safety Implications

The proposed framework separates mission switching from physical relocation. If the hub remains in place, changing the service mission requires primarily EMS-level reconfiguration. If the hub is moved, transportation, physical setup, protective bonding, deployment-specific earthing, and safety verification are required before energization.

4.6 Engineering Significance

The results support three principal observations. First, the three missions have materially different energy characteristics. Second, mission-aware energy management provides an alternative to simply increasing PV and battery capacity at a small and explicitly quantified reliability cost rather than a free improvement. Third, reconfigurability itself becomes an engineering resource. Instead of maintaining separate energy systems for agricultural, healthcare, and emergency applications, a common PV–BESS backbone can be reassigned according to the current mission.

The contribution is therefore not the physical invention of mobile PV–BESS equipment. The contribution lies in the formalization and preliminary quantification of mission-aware service reconfiguration within a deployable rural energy hub, together with deployment-specific electrical safety verification.

5. CONCLUSION AND FUTURE WORK

This study presented a mission-aware engineering framework for a deployable PV–BESS energy hub intended to provide changing critical services in rural Nigeria. The framework combines a common renewable-energy and storage backbone with mission-dependent load prioritization, supervisory energy management and deployment-specific electrical safety verification.

Unlike conventional fixed-purpose rural energy systems, the proposed hub can be configured for agricultural, healthcare or emergency operation without replacing its fundamental generation and storage infrastructure. Unlike mobile-energy-storage research primarily concerned with routing, restoration, or pre-positioning, the proposed framework focuses on how the service configuration of a common energy asset can change when its mission changes.

The preliminary simulation indicates that the mission-aware configuration can provide approximately 99% or greater critical-service coverage under the three mission states while requiring approximately 22 kWh of battery storage compared with 24 kWh for the conventional deployable benchmark, an approximately 8.3% reduction in nominal storage capacity, accompanied by a 0.65-percentage-point reduction in worst-case coverage under the assumed conditions. This trade-off, rather than a uniform improvement, is the honest characterization of the result.

The study further establishes deployment safety as an integral component of the framework. A relocated hub is not considered ready for operation until its protective bonding, deployment-specific earthing, and electrical safety verification have been completed.

The findings should nevertheless be interpreted as a preliminary engineering assessment rather than field-validated optimization. The current model uses planning-level mission profiles, assumed component costs, and a preliminary deterministic solar-resource representation. Further work will therefore incorporate site-specific Nigerian solar-resource data, measured or validated agricultural and healthcare load profiles, battery degradation, component replacement, sensitivity analysis, and uncertainty in solar availability.

Future development should also include detailed electrical design of the protective system, including inverter earthing topology, protective-device coordination, equipotential bonding, surge protection, earth-electrode arrangement, and commissioning procedures. Hardware-in-the-loop testing and eventually field demonstration will be required to validate the mission-transition logic, deployment sequence, and safety-verification procedure.

The framework ultimately shifts the concept from portable electricity provision to mission-adaptive critical service provision. Such an approach could allow one deployable renewable-energy asset to support productive rural activity during normal conditions and rapidly redirect its energy resources toward healthcare or emergency services when community priorities change.

As an immediate next step, a follow-up study will incorporate NASA POWER solar-irradiance data and validated agricultural and healthcare load profiles for the Ibese-Imasayi corridor, Ogun State, Nigeria, together with a sensitivity analysis of the ϵ -constraint thresholds and component-cost assumptions, to move the framework from a preliminary planning-level assessment toward a site-validated deployment case.

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