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# Off-Grid Power Architectures for Remote and Edge Data Centers in Energy-Constrained Environments: A Technical, Economic, and Resilience-Centered Research Review

**Samuel N Nimaful , Augustine Hanyabui, Joel Holison**
Eastern Illinois University

**Abstract- — Remote and edge data centers are increasingly deployed in locations where grid power is unavailable, unreliable, capacity-constrained, or prohibitively expensive. In these contexts, "off-grid" practicalities are less about complete electrical isolation than about assured energy autonomy: the ability to maintain service-level objectives (SLOs) and critical uptime during prolonged power interruptions, fuel supply disruptions, and extreme environmental conditions. Achieving this autonomy requires power architectures that integrate dispatchable generation (diesel or gas gensets and/or fuel cells), variable renewable energy (VRE) resources (solar PV, wind, and in some locations hydro), energy storage (UPS and BESS), robust power electronics (including grid-forming inverter-based resources), and supervisory energy management systems (EMS) that co-optimize reliability, cost, and emissions. This paper addresses the research problem: How can off-grid power systems for remote and edge data centers be architected and operated to meet high availability targets under energy constraints while minimizing lifecycle cost and carbon emissions? It synthesizes standards-body guidance, government laboratory research, recent peer-reviewed literature (2016–2026), and vendor technical documents into design patterns, a quantitative comparative model, and actionable deployment guidance. Key findings are as follows. First, microgrids structured around a formal controller specification (e.g., microgrid controller functional requirements in IEEE microgrid-controller standards) provide an engineering basis for predictable islanded operation, black start, and coordinated dispatch across distributed energy resources (DER). [1] Second, hybridization is the dominant pathway for energy-constrained environments: diesel-only designs are simple but are exposed to fuel logistics, price volatility, and emissions; adding renewables and storage materially reduces fuel burn and can improve resilience by reducing the frequency and severity of fuel-delivery dependency—an especially salient risk in remote microgrids where delivered diesel electricity can be extremely costly. [2] Third, for off-grid stability and fast contingency response, inverter-based resources and their protection/control behaviors (grid-forming operation, current limiting, and black-start behavior) are increasingly central, especially as renewable penetration rises. [3] Fourth, safety and compliance for stationary storage (e.g., fire and thermal-runaway propagation testing and installation codes) are not peripheral—they shape siting, enclosure design, and permitting timelines and thus can dominate schedule risk. [4] Quantitatively, a parametric cost-and-carbon model demonstrates that (i) LCOE and emissions are strongly driven by delivered fuel price and renewable fraction, and (ii) heavier "soft costs" and integration overhead penalize very small deployments unless modularized and standardized. Using published CAPEX/O&M baselines for PV, wind, BESS, and gensets, and modeling three load scenarios (low/medium/high) with sensitivity to delivered diesel price, the modeled LCOE ranges from roughly $0.20–$0.70/kWh depending on architecture and fuel price, while carbon intensity ranges from ~0.26–0.74 kg $CO_2$/kWh as renewable delivered share rises from ~0% to ~65%. [5] Finally, three geographically diverse real-world examples illustrate the range of viable approaches: a gas-generator solution for a large Lagos data center where grid reliability was insufficient; a fuel-cell-powered containerized edge data center integrated with district heating in northern Sweden; and an Alaska edge deployment co-located with hydropower and backed by advanced microgrid modernization efforts—each reflecting different constraints and resource endowments. [6]**

**Keywords— Key themes in this work include off-grid data centers, energy autonomy, and microgrid architectures guided by standards such as IEEE frameworks. Central concepts are hybrid power systems combining diesel or gas generators, fuel cells, and variable renewable energy (VRE) like solar PV and wind, supported by battery energy storage systems (BESS) and UPS. The paper emphasizes grid-forming inverters, energy management systems (EMS), and black-start capability for resilience. It also highlights fuel logistics risks, levelized cost of energy (LCOE), carbon emissions reduction, and lifecycle cost optimization, alongside safety standards for energy storage, thermal runaway mitigation, and modular deployment strategies for remote and edge environments.**

# I. INTRODUCTION

Remote and edge data centers are deployed to reduce latency, increase data sovereignty, support critical industrial or public services, and extend digital infrastructure to underserved regions. Yet these deployments often occur in energy-constrained environments characterized by one or more of the following: (a) absent grid infrastructure (true off-grid), (b) weak or intermittently available grid supply, (c) limited grid capacity that cannot absorb incremental load, (d) extreme fuel logistics constraints (seasonal access, limited transport windows, or security risks), and (e) regulatory or permitting barriers that limit conventional backup generation runtime. These factors force a design shift away from "backup power" toward primary power system engineering, where the energy system is integral to the facility's operational capability. [7]

**Scope**

This paper focuses on off-grid power architectures for remote and edge data centers, emphasizing the electrical supply chain from generation through conversion, storage, control, and delivery to IT loads. The scope includes: microgrids; hybrid renewable energy systems (solar PV, wind, small and medium hydropower); diesel and gas gensets; fuel cells; battery storage (UPS and BESS); energy management systems, demand response and load flexibility; power electronics; quantitative evaluation of cost, reliability, and emissions; case studies; resilience and cybersecurity; O&M; and policy/financing mechanisms. [8]

The scope excludes detailed civil engineering (foundations, geotechnical, acoustics), detailed thermal plant engineering beyond energy-relevant interactions, and region-specific legal advice. Nonetheless, major code, standard, and regulatory patterns are summarized to inform design decisions. [9]

**Research questions**

This review is organized around the following research questions:

- Architecture: What off-grid power architectures best balance reliability, cost, and emissions for remote and edge data centers across variable loads and resource endowments? [10]
- Modeling: How can designers quantify energy balance, reliability (e.g., N-1/N+1, MTBF/MTTR-based availability), CAPEX/OPEX, LCOE, and carbon emissions in a way that supports defensible decisions? [11]
- Control and power electronics: What controls and inverter/power-electronics requirements become dominant as renewable penetration increases and inertia decreases? [12]
- Resilience and cybersecurity: What are the key failure modes (fuel supply, weather, cyber-physical threats) and how should architectures mitigate them? [13]
- Deployment and governance: What operational, regulatory, and financing mechanisms most influence project success in constrained environments? [14]

# II. LITERATURE REVIEW

**Microgrids and hybridization as the dominant paradigm**

A microgrid is generally characterized as a controllable entity capable of operating connected to a grid or in islanded mode, coordinated by a microgrid controller, with generation capacity sufficient to supply critical load during islanding. The microgrid controller specification and testing standards ecosystem—centered on microgrid controller functional requirements and associated implementation/testing recommendations—provides a design anchor for dispatch, transitions between modes, black start sequencing, and safety logic. [15]

In energy-constrained environments, microgrids are rarely "renewables-only" because prolonged low-resource events (solar seasonal minima, wind lulls, hydrology variability) can be longer than economically feasible battery durations. Consequently, hybrid power systems—renewables plus storage plus dispatchable generation—are extensively modeled and deployed in remote contexts to reduce imported fuel while preserving reliability. Techno-economic studies and national-lab programs focusing on remote microgrids (e.g., Alaskan villages) emphasize pathways to substantial fuel reduction when renewables and storage are integrated with diesel, while recognizing that controls, protection, and community operational readiness are often binding constraints. [16]

For data centers, the hybridization imperative is intensified by stringent uptime and power-quality requirements, and by the load's relative inflexibility compared to many building loads. Yet emerging research demonstrates that data centers can provide meaningful flexibility (workload shifting, coordinated UPS/BESS dispatch, cooling system modulation) when properly controlled, thereby improving both economics and resilience in microgrid operation. [17]

**Solar, wind, and hydro in off-grid systems**

Solar PV is frequently the most logistically scalable VRE in remote deployments because it can be modular, container-compatible, and relatively low-maintenance. Cost and performance baselines for PV (CAPEX, fixed O&M, and capacity factor ranges) are routinely published for utility-scale projects; representative recent baselines identify PV plant overnight capital costs on the order of ~$1.4–$1.6/W_AC (U.S. reference projects) with fixed O&M on the order of tens of dollars per kW-year, while capacity factors vary substantially with resource class (e.g., ~21%–34% in modeled classes for tracking systems). [18]

Wind can materially improve seasonal complementarity and reduce storage requirements when wind regimes correlate weakly with solar availability. A recent wind cost and performance review provides a representative land-based wind reference project with CAPEX around ~$1,968/kW, OpEx around ~$43/kW-year, and net capacity factor near ~46.9% at a reference site, illustrating why wind can be highly attractive where the resource is strong. [19] The principal limitations for edge deployments are site constraints (setbacks, icing, transport and crane availability, noise), and maintenance logistics for large rotating machinery in remote environments. [20]

Hydropower—especially run-of-river and small hydro—can be uniquely valuable for remote data centers because it can provide high-capacity-factor renewable baseload, reducing the need for large storage and minimizing generator runtime. However, hydropower is site-specific and can introduce its own resilience concerns (seasonal hydrology, icing, sedimentation, fish passage constraints, and permitting). Cost/performance baselines for hydropower are treated separately from wind/PV in technology baselines, reflecting wide variability in site characteristics. [21]

**Diesel and gas gensets**

Diesel gensets remain widely used in remote and mission-critical power systems due to high power density, mature service ecosystems, and strong transient response characteristics. Yet they introduce (i) high OPEX where delivered fuel is expensive, (ii) emissions and permitting constraints, and (iii) operational risk associated with fuel quality management and storage. A government report summarizing remote isolated power systems finds diesel-generated electricity costs in remote Alaska ranging roughly from ~$0.50 to >$1.00/kWh, illustrating how fuel logistics dominate economics in many off-grid environments. [22]

Natural gas gensets (pipeline gas, LNG/CNG, or biogas in some cases) can offer lower fuel cost and lower $CO_2$ emissions per kWh than diesel when gas is available, but their feasibility is constrained by fuel infrastructure availability, methane management, and emissions-control requirements. A national-lab analysis comparing diesel and natural gas backup generators provides illustrative installed capital cost assumptions (e.g., $800/kW diesel vs. $1,000/kW natural gas) and notes meaningful lifecycle ownership costs from non-fuel O&M, as well as maintenance considerations unique to diesel fuel storage. [23]

Regulatory constraints for internal combustion engines are non-trivial in many jurisdictions. In the United States, stationary compression ignition engines and spark ignition engines used for non-emergency operation fall under specific federal standards of performance, with differentiated requirements for emergency and non-emergency use. [24] In the European Union, engine emissions requirements for non-road mobile machinery have evolved through staged standards (including Stage V), influencing the selection and after-treatment requirements for generator sets, particularly in mobile or modular deployments. [25]

**Fuel cells and hydrogen-enabled systems**

Fuel cells are re-emerging as data center power technologies in two roles: (a) prime/primary power in gas-available settings and (b) extended-duration backup as a diesel replacement pathway, particularly through hydrogen. Vendor and government materials document recent multi-megawatt demonstrations of hydrogen fuel cell backup power integrated with battery systems and microgrid controls to support data center critical loads during simulated long-duration events. [26] Fuel cell performance depends strongly on technology and fuel. Solid oxide fuel cells (SOFC) are frequently cited as achieving high electrical efficiency; for example, vendor disclosures describe ~60% electrical efficiency for a hydrogen-capable SOFC platform, which is relevant because higher electrical efficiency directly lowers fuel consumption and thus can improve both cost and emissions (subject to hydrogen carbon intensity). [27]

However, hydrogen introduces constraints that are particularly consequential in remote deployments: fuel supply chain availability, storage modality (compressed gas vs. liquid), footprint, safety case engineering, and regulatory acceptance. Government and safety-focused publications emphasize that non-technical barriers (hydrogen cost, availability, safety setbacks, and balance-of-plant constraints) remain significant adoption challenges, particularly for high-power density installations. [28]

**Battery storage, UPS, and grid-forming capability**
Energy storage plays at least three roles in off-grid data center architectures: (i) ride-through (UPS function) to bridge transfer times and power transient events, (ii) spinning reserve replacement to reduce generator starts and support load steps, and (iii) energy shifting to increase renewable utilization. Storage technology baselines highlight cost and performance trajectories for 4-hour lithium-ion systems and recommend parameter values for modeling. A recent national-lab report provides a 2024 starting overnight capital cost estimate on the order of ~$334/kWh for a 4-hour lithium-ion system, with recommended modeling assumptions including ~85% round-trip efficiency, near-zero variable O&M, and fixed O&M scaled as a percentage of power capacity to represent degradation management/augmentation. [29]

Safety standards and fire-code requirements strongly shape storage deployment design. UL thermal runaway testing methods are explicitly referenced for due diligence and are embedded into broader installation standards for stationary energy storage systems. [4] For containerized deployments, this affects spacing, ventilation, detection/suppression, and emergency response integration—often a schedule-critical path. [30]

Energy management systems, demand response, and flexibility
Energy management for off-grid microgrids requires coordinated scheduling and dispatch across resources and loads. Standards for energy management systems provide organizational frameworks for systematic energy performance improvement, while automated demand response standards provide interoperable communication models for DR signaling in grid-interactive contexts. [31] Although off-grid environments lack an ISO/utility DR market signal, the same control concepts apply internally: load shaping to reduce peak generator capacity requirements; thermal inertia exploitation (cooling setpoint modulation); and workload scheduling to align compute intensity with renewable availability. This is increasingly studied in the broader literature on industrial demand response and data-center flexibility. [32]

A foundational study analyzing demand response and OpenADR opportunities for data centers identifies DR-relevant data center loads and control opportunities, supporting the claim that data centers can be controllable loads given adequate instrumentation and automation. [33] More recent work extends these ideas toward grid-interactive “data center as a resource” platforms, indicating how BESS and coordinated controls can create fast demand response and resource adequacy value. [34]

**Power electronics, grid-forming inverters, and protection**
As renewable penetration increases and synchronous inertia declines, microgrid stability depends increasingly on inverter behavior. Modern research and standards-oriented discussions emphasize the distinctive role of grid-forming inverter-based resources in black start capability, weak-grid operation, and system strength support. [35] A related technical challenge is overcurrent limitation and fault behavior for grid-forming inverters, which affects protection coordination and post-fault recovery—issues that are especially important in islanded systems with high IBR penetration. [36]

Data center performance, efficiency, and availability standards
Data center energy performance commonly uses standardized KPIs such as Power Usage Effectiveness (PUE). International standards explicitly define PUE and specify consistent measurement and reporting, enabling more defensible comparisons across sites and architectures. [37] Data-center facility and infrastructure standards provide general concepts and classification models spanning availability, physical security, and energy efficiency enablement, supporting a risk-based approach to infrastructure planning. [38]

For availability-oriented topology classification, industry standards differentiate tiers based on redundant capacity components and distribution paths, providing a practical mapping between redundancy design (N, N+1, 2N, etc.) and expected performance outcomes. [39]

## III. METHODOLOGY

**Data sources and selection criteria**
This research used a structured document review and synthesis approach emphasizing primary and authoritative sources. Sources were prioritized as follows: (a) government laboratory and agency reports (e.g., U.S. national laboratories, DOE), (b) standards bodies and code organizations (IEEE, ISO/IEC, NFPA, UL), (c) peer-reviewed articles (2016–2026), and (d) vendor technical white papers and case studies with clearly stated assumptions or real deployment details.

Representative cost and performance baselines were drawn from (i) technology baseline sources for PV (CAPEX/O&M/capacity factor), (ii) a wind cost and performance review for land-based wind reference project CAPEX/OpEx and capacity factor, (iii) battery storage cost projection work for 4-hour lithium-ion systems including recommended efficiency and O&M modeling parameters, and (iv) a national-lab generator fuel-choice analysis for genset CAPEX/O&M and lifecycle modeling assumptions. [40]

Operational and regulatory considerations were supported by sources describing remote microgrid economics, fuel-delivery costs, emergency power system performance expectations, stationary engine regulations, and energy storage safety/testing requirements. [41]

**Modeling approach and assumptions**
The quantitative component uses a parametric annualized techno-economic model. It is designed for comparative insight rather than final engineering procurement. The model evaluates architecture options across three load scenarios, computes energy balance, annualized cost, LCOE, and $CO_2$ emissions, while treating region and load profile variability via sensitivity parameters (capacity factors and delivered fuel price).

**Load scenarios**. Three average IT load scenarios were modeled: low (50 kW), medium (250 kW), and high (1 MW). Total facility load was modeled using PUE = 1.35, consistent with the use of standardized PUE concepts and common reporting practice. [42]

**Sizing and redundancy**. Dispatchable generation was sized to support the full critical load under renewable scarcity, with N+1 redundancy implemented as two gensets each able to carry peak facility load (peak modeled as 1.2× average). This reflects a conservative "critical load must be served even with one unit out" interpretation consistent with tiered and redundant-capacity concepts. [43]

**Renewables and storage**. PV and wind capacities were sized to deliver target annual renewable shares (nominally 40% and 70% before losses) using representative capacity factors and a simplified delivered-energy factor to reflect conversion losses and curtailment. PV baseline cost and capacity factor variability were grounded in technology baselines; wind CAPEX/OpEx and net capacity factor were taken from a recent wind review reference project. [44] BESS duration was set to 4 hours of average facility load with round-trip efficiency ~85% and O&M treatment per a national-lab cost projection report. [29]

**Fuel consumption and emissions**. Diesel fuel consumption was approximated using manufacturer-style fuel consumption charts; a representative point implies ~0.072 gal/kWh at ~75% loading for a 1 MW-class unit. [45] Diesel $CO_2$ emissions were modeled using published emissions coefficients by fuel. [46]
Discounting and asset lives. Annualization used a real discount rate of 6% and representative asset lifetimes (PV 30 years, wind 25 years, genset 20 years, Li-ion BESS 15 years). Generator lifecycle assumptions align with national-lab generator analyses that apply 20-year useful life and explicit discounting. [47]

**Reliability Modeling Framework**

Reliability is treated using two complementary methods:

Topology-level redundancy reasoning (N, N+1, 2N) aligned with data-center infrastructure practice and tiered topology logic. [48]

Availability calculations based on MTBF and MTTR, using standard availability relationships (e.g., availability measured via MTBF/(MTBF+MTTR)) and series/parallel combinations, as documented in reliability/availability engineering guidance. [49]

The paper presents quantitative examples using illustrative MTBF/MTTR inputs (clearly identified as examples), because component-specific failure/repair datasets are often proprietary and highly dependent on maintenance regimes. [50]

**Technical Architectures and Design Options**
Reference architecture families
Off-grid data center power architectures can be organized into five recurring families. Table 1 summarizes these families and the dominant design trade-offs.

**Table 1**
**Taxonomy of off-grid power architectures for remote and edge data centers (conceptual comparison)**

| Architecture family | Typical components | Strengths | Primary risks / constraints | Best-fit contexts |
|---|---|---|---|---|
| Diesel-only island plant | N+1 diesel gensets, ATS/switchgear, UPS (minutes) | Mature, high power density, fast procurement | High fuel OPEX and logistics risk; emissions and runtime permitting constraints | Very small or temporary deployments; extreme schedule urgency |
| Hybrid PV + BESS + diesel | PV, 4–8h BESS, N+1 diesel, microgrid | Major fuel reduction; quieter operation; | BESS safety/permitting; PV seasonal variability | Solar-viable sites with expensive delivered fuel |

| Architecture family | Typical components | Strengths | Primary risks / constraints | Best-fit contexts |
|---|---|---|---|---|
| | controller | improved resilience to fuel disruptions | | |
| Hybrid PV + wind + BESS + diesel | PV, wind, BESS, N+1 diesel, grid-forming inverter controls | Higher renewable share; improved seasonal complementarity | Wind logistics/maintenance; icing/noise constraints | Wind-strong sites and year-round operation |
| Gas genset microgrid | N+1 natgas/biogas gensets, UPS/BESS, controls | Lower $CO_2$ per kWh than diesel; potentially lower fuel cost | Requires gas supply infrastructure; methane/safety governance | Pipeline/CNG/LNG accessible sites; industrial campuses |
| Fuel cell–centric microgrid | Fuel cell plant (SOFC/PEM), BESS, potentially PV/wind | Low criteria pollutants; high efficiency; potential diesel replacement | Hydrogen logistics; safety case; CAPEX uncertainty | Where hydrogen/biogas is available, or sustainability mandates dominate |

This taxonomy reflects recurring design patterns seen in microgrid standards frameworks, remote microgrid fuel-reduction programs, and data-center-specific evaluations of diesel replacement options. [51]

**Electrical topology and coupling choices**

AC-coupled vs. DC-coupled hybrids. AC-coupled architectures integrate PV/wind via inverters onto an AC bus shared with gensets and loads; DC-coupled architectures may integrate PV and BESS behind a shared DC bus and invert to AC for facility distribution. Architectures are selected based on controllability, fault behavior, conversion losses, and ease of integrating legacy gensets. For remote deployments, AC coupling is common because it aligns with conventional genset and switchgear ecosystems, while DC coupling can be advantageous for high-renewables and fast control but requires more careful protection design. These trade-offs intensify as IBR penetration increases and grid-forming behavior becomes central. [12]

Grid-forming inverter requirements. High-renewable islanded microgrids frequently require grid-forming control to establish voltage and frequency references, support black start, and stabilize weak-grid conditions. Recent technical literature emphasizes that black-start capability, current limiting, and protection co-design are key barriers and active research areas for inverter-dominated systems. [52]

**Energy management and dispatch control strategies**

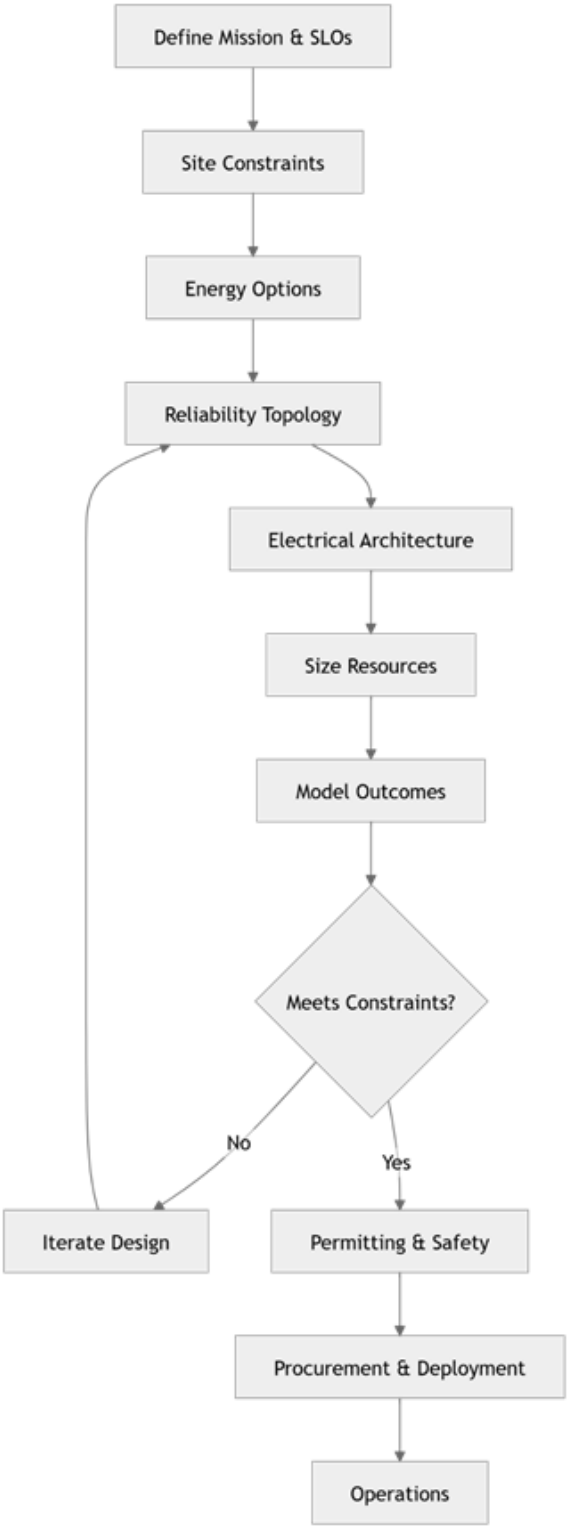
A microgrid EMS typically implements forecast-aware dispatch under constraints (state-of-charge bounds, generator minimum loading, ramp rates, reserve requirements, and power-quality constraints). The literature on hybrid renewable microgrids and HRES energy management emphasizes the importance of dispatch strategies (e.g., load-following vs. cycle-charging philosophies, multi-objective optimization, and robust control under uncertainty) for minimizing cost while maintaining reliability. [53]

For data centers, EMS must additionally integrate with IT and cooling orchestration to treat the full facility as a cyber-physical system. Standards for energy management systems offer organizational-level structure for continuous improvement; data center-specific studies show how microgrid modeling and resilience evaluation can incorporate outages and recovery constraints. [54]

**Decision process flowchart**

The following flowchart operationalizes a practical decision process for selecting off-grid architectures in energy-constrained settings, integrating reliability requirements, resource assessment, fuel logistics, and permitting constraints.

This flow derives from microgrid controller specification concepts, data center infrastructure topology classification practices, and energy storage safety/installation requirements. [55]




**Quantitative Modeling and Comparative Results**

Energy balance equations and metrics

The model uses standard annual energy balance relationships:

Annual load energy:

$$E_{\text{load}} = P_{\text{avg}} \times 8760$$

Annual renewable energy (resource i):

$$E_i = P_i \times CF_i \times 8760 \times \eta_{\text{delivered}}$$

Fossil generation requirement (simplified):

$$E_{\text{fossil}} = E_{\text{load}} - \sum E_i \text{ (bounded below by 0)}$$

LCOE (annualized approximation):

$$LCOE \approx \frac{C_{\text{cap,ann}} + C_{\text{O\&M}} + C_{\text{fuel}}}{E_{\text{load}}}$$

These are consistent with how technology baselines discuss LCOE as a summary metric combining CAPEX, O&M, and energy production assumptions, and with national-lab modeling practices for comparing generator fuel choices and storage costs. [56]

**Scenario definitions and parameter baselines**

**Table 2**
**Modeled scenarios and key assumptions (illustrative, parameterized)**

| Category | Low load | Medium load | High load | Notes / source basis |
|---|---|---|---|---|
| Average IT load (kW) | 50 | 250 | 1000 | Modeled scenarios (design variable) |
| PUE | 1.35 | 1.35 | 1.35 | PUE is standardized in ISO/IEC KPI frameworks; value illustrative [42] |

| Category | Low load | Medium load | High load | Notes / source basis |
|---|---|---|---|---|
| Average facility load (kW) | 67.5 | 337.5 | 1350 | IT × PUE |
| Peak factor | 1.2× | 1.2× | 1.2× | Peak modeling assumption; aligns with headroom planning |
| Genset topology | 2× peak (N+1) | 2× peak (N+1) | 2× peak (N+1) | Tier topology emphasizes redundant capacity components [48] |
| PV CAPEX ($/kW_AC) | - | - | - | Uses published ATB reference pricing (e.g., ~$1.56/W_AC for 2023) [57] |
| PV CF (fraction) | 0.25 | 0.25 | 0.25 | Within published CF ranges (~21–34% for modeled classes) [58] |
| Wind CAPEX ($/kW) | - | - | - | Reference land-based wind CAPEX ~$1,968/kW [19] |
| Wind net CF (fraction) | 0.47 | 0.47 | 0.47 | Reference project net CF ~46.9% [19] |
| BESS duration | 4 h | 4 h | 4 h | Common planning duration; cost baselines for 4-h Li-ion [29] |
| BESS cost ($/kWh) | 334 | 334 | 334 | 2024 starting point for 4-h Li-ion overnight cost [59] |
| Diesel genset | 800 | 800 | 800 | National-lab assumptions |
| CAPEX ($/kW) | | | | for backup gensets [23] |
| Delivered diesel price ($/gal) | 3 / 6 / 9 | 3 / 6 / 9 | 3 / 6 / 9 | Sensitivity captures moderate vs remote delivered fuel conditions [60] |

The model additionally includes fixed "soft costs" (engineering, logistics, permitting) that scale weakly with size—reflecting the reality that remote deployments incur non-linear overhead. These are not standardized and are included to demonstrate scale sensitivity rather than to claim universal values. [61]

**Comparative results**

The model compares three representative architectures:

Diesel-only (N+1)
PV+BESS+Diesel (targeting ~40% renewable contribution before losses)

PV+Wind+BESS+Diesel (targeting ~70% renewable contribution before losses)

Fuel price sensitivity is crucial because remote delivered fuel costs dominate marginal operating economics in many isolated microgrids. [62]

**Table 3**
**Modeled comparative outcomes (selected outputs; renewable share reflects delivered energy after simplified storage losses)**

| Load scenario | Architecture | Renewable share delivered | CAPEX (approx.) | LCOE @ $3/gal | LCOE @ $6/gal | LCOE @ $9/gal | Carbon intensity (kg $CO_2$/kWh) |
|---|---|---|---|---|---|---|---|
| Low | Diesel-only (N+1) | 0.00 | $0.29M | 0.268 | 0.484 | 0.700 | 0.735 |

| Load scenario | Architecture | Renewable share delivered | CAPEX (approx.) | LCOE @ $3/gal | LCOE @ $6/gal | LCOE @ $9/gal | Carbon intensity (kg $CO_2$/kWh) |
|---|---|---|---|---|---|---|---|
| Low | PV+BESS+Diesel | 0.37 | $0.65M | 0.252 | 0.388 | 0.524 | 0.463 |
| Low | PV+Wind+BESS+Diesel | 0.65 | $0.77M | 0.213 | 0.289 | 0.365 | 0.259 |
| Medium | Diesel-only (N+1) | 0.00 | $0.99M | 0.255 | 0.471 | 0.687 | 0.735 |
| Medium | PV+BESS+Diesel | 0.37 | $2.79M | 0.239 | 0.375 | 0.511 | 0.463 |
| Medium | PV+Wind+BESS+Diesel | 0.65 | $3.40M | 0.200 | 0.276 | 0.352 | 0.259 |
| High | Diesel-only (N+1) | 0.00 | $3.50M | 0.251 | 0.467 | 0.683 | 0.735 |
| High | PV+BESS+Diesel | 0.37 | $10.72M | 0.236 | 0.372 | 0.508 | 0.463 |
| High | PV+Wind+BESS+Diesel | 0.65 | $13.17M | 0.196 | 0.273 | 0.349 | 0.259 |

**Interpretation. Several robust conclusions emerge:**

Fuel price dominates OPEX, and therefore LCOE, for diesel-heavy architectures. This aligns with empirical observations in remote microgrids where delivered diesel power costs are very high. [62]

Hybridization materially reduces carbon intensity by reducing generator runtime and fuel burn, with diminishing returns driven by curtailment and storage losses. The underlying storage efficiency and cost assumptions used here are consistent with national-lab recommended values for 4-hour lithium-ion systems. [59]

Wind becomes disproportionately valuable at high renewable targets when a strong wind resource exists, because higher net capacity factor improves energy yield per unit CAPEX relative to PV in many locations. [63]

Small deployments are "soft-cost sensitive." Non-linear overhead (engineering, permitting, logistics, and specialized commissioning) penalizes small edge sites; this motivates standardized modular designs and repeatable permitting playbooks. [64]

**Reliability analysis: N-1/N+1 and MTBF-based availability**
Topology-level reliability. In off-grid systems, N+1 generation redundancy is necessary but not sufficient: the system must also withstand failures in switchgear, protection relays, inverters, fuel systems, and controls. Tier-based topology descriptions emphasize redundant capacity components and (for higher tiers) distribution path redundancy and isolation to avoid common-cause failures. [65]

Availability example using MTBF/MTTR. Availability can be expressed as the fraction of time a repairable system is operational, commonly measured via MTBF/(MTBF+MTTR). [49] Consider an illustrative genset availability example (values chosen for demonstration): if MTBF = 1,000 hours and MTTR = 8 hours, availability of one unit is 1,000/(1,008) ≈ 0.992. With two parallel redundant units (either can carry the load), availability of the generation function becomes approximately $1 - (1 - 0.992)^2 \approx 0.99994$ (~"four nines"). This formalizes why redundancy is powerful, but it also shows that common-cause failures (shared fuel, shared switchgear) can dominate if not explicitly mitigated. [66]

Fuel as a reliability variable. For off-grid autonomy, fuel supply chain reliability is part of the reliability model: a fully redundant genset plant can still fail if fuel is unavailable. National-lab work on generator fuel choice notes that backup systems can fail due to generator failure or because the generator runs out of fuel, motivating explicit autonomy-duration requirements and fuel logistics planning. [23]

## IV. CASE STUDIES AND IMPLEMENTATION CONSIDERATIONS

Case study: Gas generator off-grid solution for a large Lagos data center
A detailed industry case study describes a power solution for a major Lagos data center where the grid was unreliable and diesel generation was the dominant power source most of the time. The case reports that the data center had previously relied

on grid plus diesel, but grid unreliability drove operation such that 95% of the time power came from a temporary diesel generator. A new solution deployed five gas generators delivering ~5 MW total site power, installed in two weeks, with stated redundancy intent and subsequent plans to add lithium-ion battery storage to further improve resilience and reduce fuel consumption. [67]

This case illustrates a common "energy-constrained grid" reality: off-grid or quasi-off-grid operation emerges not because off-grid is preferred, but because grid reliability and cost instability force on-site generation to become primary. It also highlights the practical importance of workforce training, local service capability, and logistics management in a constrained urban environment. [68]

Key transferable lessons. Gas gensets can reduce fuel cost relative to diesel where gas supply is available, but they introduce their own infrastructure dependencies. The case further supports the practice of layering BESS as spinning reserve or fast-response stabilization, providing additional resilience while enabling generator operating-point optimization. [69]

**Entities (first mention only): Aggreko[70]; MTN Nigeria PLC[71]; Lagos[72]**

**Case study: Fuel-cell CHP edge data center integrated with district heating in northern Sweden**

A research institute report describes a containerized edge data center deployment in northern Sweden powered by fuel cells rather than the mains. The system uses fuel cells as the main power source, fueled by locally produced biogas, and captures heat for integration with a district heating system—demonstrating combined heat, power, and compute (CHPC). The deployment is containerized (two containers), with the data center equipment in one and fuel cells in the other, and includes UPS backup. [73]

This case is significant because it demonstrates an architecture that can be highly attractive in cold climates where thermal energy recovery can create an additional value stream and improve overall system efficiency. It also demonstrates how "off-grid" can be reinterpreted as grid-independent primary power coupled to local energy networks. [74]

**Entities (first mention only): RISE[75]; Luleå[76]**

Case study: Hydropower-powered edge data center and advanced microgrid modernization in Cordova, Alaska

A news report describes the delivery of an edge data center module to a remote Alaskan community energy provider, deployed at a hydropower facility and described as entirely powered by the local hydro plant, with rapid deployment timelines. [77] Complementing this, a national-lab project summary describes Cordova as a remote microgrid reliant on hydropower or diesel, facing severe winter storms and other hazards, and participating in a DOE-funded microgrid modernization program using advanced sensing, control, and cybersecurity planning approaches (including a "digital twin" model and resilience-by-design). [78]

This combined evidence illustrates a particularly relevant "energy-constrained" archetype: a remote island-like microgrid with high renewable potential (hydro), seasonal load variability, and extreme-event risk, where edge computing can be co-located with generation to reduce backhaul latency while leveraging locally available renewable power. [79]

**Entities (first mention only): Cordova[80]; Cordova Electric Cooperative[81]; Greensparc[82]; Hewlett Packard Enterprise[83]**

**Resilience considerations**

Extreme weather and multi-hazard design. Remote microgrids must withstand hazards that may exceed typical facility design assumptions (storms, flooding, landslides, icing, wildfires, and seismic risk). The Cordova modernization summary explicitly notes exposure to winter storms, avalanches, and other hazards, underscoring the need for multi-hazard planning and operational rehearsals. [84]

Fuel logistics resilience. Delivered fuel may be seasonal and subject to disruption. Remote system guidance notes that fuel deliveries can be limited and vulnerable to disruptions, and delivered diesel generation may be very costly. [20] Consequently, resilience planning should treat fuel autonomy duration as a first-class requirement (e.g., "X days at peak load"), with explicit policies for fuel quality management, storage redundancy, and supply chain diversification. [23]

Black start and restart sequencing. Islanded systems require explicit black-start plans and tested sequences; microgrid controller specifications acknowledge black start as a foundational capability for microgrids designed for islanded operation. [85]

**Cybersecurity considerations for cyber-physical power architectures**

Off-grid microgrids for data centers are deeply cyber-physical: power controllers, relays, RTUs/PLCs, inverter controls, and EMS platforms expose communications surfaces that can be attacked. Smart-grid cybersecurity frameworks provide

structured guidance for risk assessment and security requirement selection for systems that are increasingly interconnected. [86]

Standards-aligned segmentation and lifecycle security. Industrial automation and control system standards emphasize a holistic cybersecurity lifecycle and define requirements and processes for secure IACS operation, while widely used interpretations emphasize architectural segmentation into zones and conduits to reduce blast radius. [87]

Protocol security. For IEC 61850-based automation (common in utility and increasingly relevant in distributed energy systems), cybersecurity standards provide key management and protection mechanisms (e.g., certificate and key handling) that are essential to hardening operational communications. [88]

Operational cybersecurity controls. In practice, best-in-class off-grid deployments typically require: strict OT network segmentation, asset inventory and continuous monitoring, secure remote access, patch governance, and incident response playbooks. These practices align with industrial cybersecurity standards and national guidance emphasizing risk-based control selection. [89]

Entities (first mention only): National Institute of Standards and Technology[90]; International Society of Automation[91]; International Electrotechnical Commission[92]

**Deployment, commissioning, operations, and maintenance best practices**

Commissioning and acceptance testing. Off-grid architectures require staged commissioning: component FAT/SAT, integrated microgrid functional testing (mode transitions, black start, island stability), and load-step testing with representative IT load blocks. In mission-critical environments, emergency power standards emphasize readiness and testing rigor for standby power systems, and microgrid-focused programs emphasize readiness exercises to validate islanding and load-carrying performance. [93]

Generator standardization and rating discipline. Correct interpretation of generator ratings for prime/standby/mission-critical duty is essential; generator rating frameworks (e.g., ISO generator set classifications and "data center mission critical" rating practices in modern datasheets) reduce operational risk and improve lifecycle planning. [94]

Battery safety and thermal management. Stationary storage must be designed for fire and thermal runaway risk. The most widely referenced approaches include large-scale fire testing standards and installation standards that drive detection, spacing, ventilation, and emergency response requirements. [95]

Spares, maintainers, and logistics. Remote deployments must explicitly plan for: spare inverter modules, power electronics boards, battery HVAC filters/parts, generator consumables (including after-treatment fluids where required), fuel quality management, and trained local technicians. The Lagos case explicitly describes local technician training and staffing as part of maintaining performance under constraints. [68]

**Policy, regulatory, and financing mechanisms**

Financing mechanisms. Off-grid and resilience-oriented microgrid projects often require blended financing and contracting structures, including energy savings performance contracts, utility energy service contracts, PPAs, grants, and other public-private mechanisms. A federal program slide deck enumerates multiple contracting and funding vehicles used to deploy resilience-focused microgrids and emphasizes planning, investment, and testing cycles. [96]

Stacking value streams. Microgrid case study research emphasizes that multiple value streams (e.g., resilience, demand response, energy arbitrage, avoided outages, and policy incentives) are frequently needed to justify installed costs, especially when storage and advanced controls are included. [97]

**Environmental and permitting constraints.** Internal combustion generation is often constrained by emissions rules and operating restrictions that differentiate emergency from non-emergency operation. These constraints can materially affect architecture decisions (e.g., whether to rely on diesel for long-duration runtime vs. transition to gas, renewable fuels, or fuel cells). [98]

**Entities (first mention only):** U.S. Department of Energy[99]; U.S. Environmental Protection Agency[100]; U.S. Energy Information Administration[101]; International Renewable Energy Agency[102]; National Fire Protection Association[103]; IEEE[104]; International Organization for Standardization[105]; Uptime Institute[106]

## V. GAPS, LIMITATIONS, AND FUTURE RESEARCH DIRECTIONS

Long-duration storage and seasonal autonomy. Most economic storage deployments remain concentrated around short durations (e.g., 4 hours), yet higher renewable penetration and

reduced fuel logistics risk can require longer duration storage, especially for multi-day weather events. National-lab work on moving beyond 4-hour lithium-ion storage highlights the growing interest and potential role of 6–10 hour (and longer) storage, suggesting a future research and deployment pivot for remote critical loads. [107]

Inverter-dominated protection and standards maturation. Microgrid standards briefings argue that microgrid control standardization depends on inverter standardization and that testing standards remain a critical bottleneck. As IBR penetration grows, rigorous, standard-aligned testing for fault behavior, black start, and protection coordination is a priority research and standardization area. [108]

Hydrogen security and lifecycle emissions. Hydrogen fuel cells can decarbonize backup power only if hydrogen supply has low lifecycle carbon intensity; remote deployments raise additional questions around hydrogen logistics security, long-duration storage safety, and resilience under disruptions. These topics require more region-specific policy analysis and empirical deployment evidence. [109]

Data center load flexibility integration. While DR and flexible scheduling research is advancing, operationalizing it in off-grid critical environments requires validated approaches to SLO-aware workload shifting, real-time telemetry integration, and formal verification of risk bounds. Recent national-lab platform development and peer-reviewed work on data center flexibility indicates progress but also identifies a research gap between theory and operations at scale. [110]

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