sustainability

MDPI

Article

Design of Microgrid-Based Resilience Solutions to Improve Public Health Impacts of Earthquake-Induced Power Outages

Süleyman Emre Eyimaya [1] and Aslıhan Öztürk Eyimaya [2,*]

[1] Department of Electronics and Automation, TUSAS-Kazan Vocational School, Gazi University, 06560 Ankara, Turkey; eyimaya@gazi.edu.tr
[2] Department of Public Health Nursing, Nursing Faculty, Ankara University, 06560 Ankara, Turkey
* Correspondence: asliozturk@ankara.edu.tr; Tel.: +90-5066844484

Abstract

Earthquakes often cause prolonged electricity outages that disrupt essential health services and basic water, sanitation, and hygiene functions in hospitals and field clinics. This study combines a focused literature review with a time-step energy balance simulation developed in MATLAB 25.2 and Simulink to examine how power interruptions translate into public health risks and to evaluate microgrid-based resilience solution designs. Conventional electricity supply with diesel backup is compared with hybrid solar power, battery storage, and diesel generator configurations under five outage scenarios that vary by duration, fuel availability, and solar conditions. The results indicate that diesel-only strategies are highly vulnerable to fuel supply disruptions, leading to substantial downtime of critical services and increased unmet essential electricity demand. Hybrid microgrid configurations demonstrated a significant improvement in critical-load continuity, thereby enhancing the capacity to sustain essential care during prolonged outages. In the fuel-constrained 72 h outage scenario (S2: 24 h diesel availability), the hospital case shows critical service availability increasing from ~48% (diesel-only) to ~87% (PV + battery + diesel), with similar improvements for the field clinic (~46% to ~85%). Hybrid microgrids improve critical-load continuity via solar generation, battery buffering, and priority-based load shedding, while reducing diesel runtime and extending fuel autonomy. The model also relates energy performance to a WASH-supportability proxy relevant to infection prevention.

Keywords: microgrid; public health; energy resilience; earthquake

1. Introduction

Large earthquakes can trigger cascading failures across interconnected critical infrastructures, with electricity disruption frequently acting as an early "multiplier" of downstream impacts. Health systems are particularly exposed because modern healthcare delivery depends on continuous electrical power for life-support equipment, diagnostic services, sterilization, information systems, lighting, heating/ventilation/air conditioning, and the cold chain for temperature-sensitive medicines and vaccines. When grid power is lost and backup systems fail or degrade, facilities may be forced to curtail services, divert patients, or evacuate—outcomes that can compromise the continuity of essential care during the acute response period and throughout recovery. These challenges align with global disaster risk reduction priorities that emphasize continuity of essential services and the protection of critical infrastructure under extreme events [1].

Check for updates

Academic Editor: Ali Bahadori-Jahromi

Received: 28 January 2026
Revised: 27 February 2026
Accepted: 4 March 2026
Published: 5 March 2026

Copyright: © 2026 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license.

Hospitals and field clinics differ in scale but share a common vulnerability: both operate as "electricity-dependent care platforms." Hospitals typically have higher and more complex loads (e.g., intensive care units, operating theaters, imaging systems), while field clinics and temporary medical sites—deployed to provide surge capacity, triage, and basic treatment—often rely on smaller, more constrained power systems with limited redundancy. Consequently, even short interruptions can translate into disproportionate service degradation in field settings. This vulnerability is amplified by infrastructure interdependencies: electricity loss can also disrupt water pumping, treatment, disinfection, sanitation services, medical waste handling, and communications, undermining infection prevention and control and safe clinical operations. Prior work on critical infrastructure interdependencies provides a useful lens for understanding how electricity disruptions propagate to dependent systems, including healthcare and water, sanitation, and hygiene (WASH) services [2,3].

The concept of "resilience" has matured in both disaster science and power systems engineering. Seismic resilience frameworks emphasize quantifying performance loss and recovery over time, and they provide the basis for comparing alternative mitigation and recovery strategies under earthquakes. In the power domain, resilience extends beyond traditional reliability metrics by focusing on high-impact, low-frequency events, adaptive operation, and recovery trajectories. However, healthcare-specific outcomes are not always explicitly represented in energy resilience studies, and health system resilience discussions may under-specify the engineering design choices that determine whether critical loads can be served under prolonged outages. This creates a practical gap: decision-makers need integrated evidence and modeling that translates outage characteristics and energy-system design assumptions into measurable indicators of continuity for essential health services, for both hospitals and field clinics [4]. More broadly, power-system resilience research emphasizes a full-cycle perspective (preparedness, absorption, and recovery) and highlights the role of flexible resources (e.g., energy storage) in supporting operation under extreme disruptions [5]. While previous studies have primarily focused on technical performance metrics of energy systems, this study uniquely integrates energy resilience modeling with public health continuity indicators and WASH service dependencies, addressing a critical gap in linking engineering solutions to health outcomes in earthquake-affected settings.

Backup diesel generators remain a dominant strategy for emergency power in many facilities. Yet generator-based continuity can be compromised by failure modes that are common after major earthquakes: fuel supply disruptions, limited on-site storage, equipment damage, insufficient maintenance, and constraints on refueling logistics. These risks motivate interest in microgrids—localized energy systems capable of operating grid-connected or islanded—configured to supply critical loads using combinations of distributed generation and energy storage [6–8]. Microgrid research has produced mature control and operation concepts (e.g., hierarchical control, droop-based strategies, coordinated dispatch), and a growing body of standards supports interoperability and grid integration. When designed for resilience, microgrids can reduce dependency on fuel logistics by incorporating photovoltaic (PV) generation and batteries, while still retaining dispatchable sources where needed [9]. Recent studies show that declining rotational inertia increases stability challenges and motivates inverter-based resources (including grid-forming storage) to provide frequency-support services, with implications for microgrid dispatch and scheduling under disturbances [10].

In disasters such as earthquakes, power outages have serious impacts on critical infrastructure such as the continuity of healthcare services and water supply. One study indicated that power outages threaten the uninterrupted operation of critical loads in hospitals (life support systems, drug cooling, operating room equipment) and directly

affect patient care [11]. Uninterrupted power supply is vital, especially for intensive care units and surgical procedures. It has been observed that traditional diesel generators are insufficient during prolonged outages due to their limited fuel capacity and maintenance problems [12]. Damage to water networks after earthquakes and the disabling of pumping stations due to power outages prevent the supply of clean water, leading to deterioration of hygienic conditions and an increased risk of epidemic diseases [13].

The use of microgrid systems in hospitals and critical infrastructure is becoming increasingly common to ensure energy continuity. One study showed that a hybrid microgrid consisting of a photovoltaic system, an energy storage system, and a backup diesel generator could withstand an average grid outage of 72 h and provide the hospital with a net energy resilience of 24 h [14]. These types of systems can operate independently in "island mode," providing power off the grid and guaranteeing uninterrupted supply to critical loads [15]. Microgrids integrated with renewable energy sources (solar panels) and energy storage systems (batteries) provide economic advantages by reducing energy costs not only during disasters but also during normal operation [16].

In earthquakes, the structural integrity of hospital buildings, as well as the resilience of energy and water infrastructure, becomes crucial. One study reported that power and water outages were among the leading causes of hospital evacuations after earthquakes, halting the operation of medical equipment and disrupting essential services such as sterilization [17]. Recent seismic resilience assessments of water distribution networks have shown that earthquake-induced pipe ruptures, combined with power outages at pumping stations, can lead to water service disruptions above normal capacity and seriously jeopardize post-disaster recovery efforts [18]. In this context, integrated microgrid systems specifically designed for healthcare facilities offer comprehensive resilience by ensuring uninterrupted power supply for critical medical equipment while simultaneously supporting water pumping and purification systems essential for sanitation and patient care [19]. Recent literature emphasizes that incorporating the economic value of energy resilience—quantified through metrics like Value of Lost Load—into microgrid investment cost–benefit analyses significantly enhances their economic justification, making such systems financially viable not only during disaster scenarios but also in normal operational conditions [20].

For healthcare, microgrid value is best assessed not only in kWh served, but in health-service continuity terms: the ability to sustain time-critical functions (e.g., emergency surgery, ventilation, diagnostics), maintain safe environmental conditions, preserve the cold chain, and support minimum WASH functions necessary for safe care delivery. WASH-related dependencies are especially important during disasters because inadequate water and sanitation can increase infection risks and undermine clinical quality. Global guidance and baseline assessments underscore persistent gaps in WASH services in healthcare facilities and highlight the critical role of reliable infrastructure in enabling safe care [21,22]. From a humanitarian response perspective, minimum standards further reinforce the need to ensure basic water, sanitation, and hygiene conditions during emergencies.

Existing solutions (diesel backup, PV + storage, and microgrids) are briefly reviewed first, followed by their practical limitations under earthquake conditions (fuel logistics, sizing uncertainty, operational protocols, and WASH-dependent loads). We then state the research gap and summarize our contributions: an integrated evidence-to-model pathway, a tiered healthcare/WASH continuity framing, and scenario-based comparative results.

Against this backdrop, two methodological needs emerge. First, the literature spanning earthquake impacts on healthcare operations, power disruptions, and facility service failures is heterogeneous—ranging from case reports to engineering analyses—making it well-suited to scoping review methods that map evidence, identify recurring failure modes,

and summarize reported consequences for service continuity [23,24]. Second, actionable design guidance benefits from scenario-based modeling that can evaluate microgrid configurations and load prioritization strategies under earthquake-induced blackout conditions and plausible constraints (e.g., fuel scarcity) continuity [25,26]. Importantly for reproducibility and accessibility, such modeling can be implemented in MATLAB/Simulink using a time-step power-balance approach, without requiring specialized power electronics simulation add-ons, while still enabling rigorous comparison across scenarios and continuity metrics.

The analytical scope encompasses two primary healthcare contexts frequently implicated in earthquake response: (i) acute care hospitals and (ii) field clinics or temporary medical facilities. Hospitals are modeled as multi-service facilities with stratified load categories—including life support, emergency theaters, diagnostics, and essential support—while field clinics are conceptualized as lower-capacity, modular care points with smaller power demands but reduced redundancy. This dual focus reflects empirical findings that both established and rapidly deployed facilities experience electricity-driven constraints during major earthquakes. Within these facilities, the study focuses on the continuity of "essential health services" (EHS), such as emergency, critical, and neonatal care. To operationalize this, loads are grouped into four functional tiers: (1) critical clinical loads, (2) high-priority diagnostic and support loads, (3) energy-dependent WASH functions (e.g., water pumping and disinfection), and (4) non-critical or deferrable loads. The simulation model respects this hierarchy through a load-shedding and restoration logic designed to maintain critical clinical and WASH functions as long as feasible under resource constraints.

The scope explicitly includes energy-dependent WASH functions within healthcare facilities, acknowledging that safe water, sanitation, and hygiene are foundational enablers of quality care and infection prevention. While community-level WASH systems are outside the direct modeling boundary, the framework allows for representing a minimal "safe water support" load required for the facility to meet basic standards under emergency conditions. By linking these facility and service categories to outage characteristics and microgrid configurations, the study aims to bridge detailed engineering modeling with health-oriented continuity metrics that are meaningful for both energy planners and health-system decision makers.

The transferable novelty of this research lies in the formalization of a tiered load prioritization framework that maps technical energy-balance dynamics directly to clinical service continuity levels. By providing a reproducible dispatch algorithm and a standardized WASH-supportability proxy, this study offers a modular benchmarking tool moving beyond site-specific scenario analysis. This study contributes an integrated "evidence + model" framework for earthquake contexts by: (i) synthesizing published evidence on how earthquake-induced power outages disrupt hospitals and field clinics, including cascades to WASH-relevant facility services; (ii) formalizing an impact pathway from outage characteristics to measurable continuity proxies for essential health services; and (iii) evaluating, via MATLAB/Simulink scenario modeling, how microgrid architectures and load prioritization strategies can reduce critical service downtime and unmet critical energy demand relative to conventional backup approaches.

This study has been repositioned as an integrated evidence-based model framework that translates interruption characteristics into healthcare continuity indicators (including WASH backlog payloads) and enables repeatable scenario-based comparisons of backup architectures. Public-health impacts are not modeled epidemiologically; instead, we use service-continuity and WASH-supportability proxies to represent operational conditions that enable safe care. Claims are now restricted to continuity improvements rather than quantified health outcomes. Furthermore, this study enhances the scientific rigor of re-

silience modeling by formalizing the dispatch logic into a reproducible algorithm and providing a quantitative sensitivity framework to assess the impact of technical uncertainties on healthcare continuity metrics.

The remainder of this paper is organized as follows: Section 2 summarizes the public health consequences of earthquake-related power disruptions in healthcare facilities and associated WASH systems. Section 3 reviews microgrid-based resilience solutions for healthcare facilities, with an emphasis on hybrid PV–battery–diesel configurations and load-prioritization strategies. Section 4 describes the proposed microgrid design and the MATLAB/Simulink time-step power-balance simulation framework, including key assumptions, load-tier definitions, and performance metrics. Section 5 presents the simulation scenarios and comparative results for the hospital and field clinic case studies. Finally, Section 6 concludes with design-oriented recommendations and directions for future work.

2. Public Health Consequences of Earthquake-Related Power Disruptions in Healthcare and WASH Systems

Major earthquakes frequently trigger multi-day electricity disruptions due to transmission and distribution damage, substation failure, and cascading infrastructure impacts [27]. From a public health perspective, these outages matter not only because they interrupt "power," but because they rapidly degrade the functional capacity and safety of healthcare delivery and WASH services [28]. Hospitals and temporary facilities rely on electricity for life-support equipment, operating theaters, imaging and laboratory diagnostics, sterilization and HVAC, cold-chain storage, communications, and electronic information systems; meanwhile, water abstraction, pumping, pressure management, storage, and (where available) treatment/disinfection are also power-dependent [29]. Consequently, even where buildings remain structurally intact, loss of electricity can convert a nominally "standing" facility into a partially or non-functional service node, with downstream risks of avoidable mortality, complications from delayed treatment, and increased infection risk in crowded post-disaster settings.

2.1. Hospitals

Hospitals are among the most electricity-intensive public service assets and their performance during earthquakes is often constrained by non-structural and system-level failures rather than by complete structural collapse. Post-earthquake assessments repeatedly report that disruption of internal distribution (switchgear, panels, transfer switches), backup generator faults, inadequate maintenance/testing, and fuel system vulnerabilities can curtail functionality, trigger evacuations, and force patient diversion. Because electricity underpins intensive care, emergency surgery, obstetric and neonatal care, dialysis, and diagnostic services, even short interruptions can produce cascading clinical consequences, including canceled procedures, closure of critical units, and impaired triage and referral coordination. Resilience frameworks for health facilities therefore treat reliable power and redundancy as foundational: the WHO Hospital Safety Index explicitly includes electrical power and backup systems because failure in these components can negate other safety investments and undermine life-saving capacity during seismic emergencies [30].

2.2. Field Clinics and Temporary Facilities

Field clinics and temporary medical facilities are deployed to absorb surge demand, provide triage, and restore coverage when hospitals are damaged or inaccessible [31]. Their effectiveness is typically shaped by energy continuity under logistical constraints: power is often supplied by portable generators or small autonomous systems operating with limited spares, uncertain fuel resupply, and high sensitivity to equipment failure. In practice,

inadequate power directly limits lighting for night operations, basic diagnostics, minor procedures, refrigeration and cold-chain integrity, and communication with referral hospitals and emergency operations centers, degrading both care quality and coordination. These constraints are widely documented in humanitarian and emergency medical guidance, which highlights the central role of reliable power for temporary health service delivery in complex emergencies and disasters.

2.3. Water Supply and Basic WASH Services

Electricity disruptions also create public health risks by degrading WASH conditions within health facilities and the surrounding community. Healthcare facilities depend on electricity for water abstraction, pumping and pressure maintenance, storage, and (in some contexts) treatment and disinfection. Earthquake-induced outages can therefore interrupt internal water supply even when parts of the external network remain partially functional, undermining hand hygiene, environmental cleaning, sterilization, sanitation systems, and safe waste management. Global evidence indicates that many facilities already lack basic WASH under routine conditions, implying limited redundancy during disasters and making outage-induced WASH failures especially consequential. International standards (e.g., Sphere) and WHO technical guidance emphasize that adequate water quantity and quality, together with sanitation and hygiene services, are essential for infection prevention and control (IPC) and for safe delivery of emergency and routine care—particularly in crowded post-disaster contexts where transmission risk rises [32].

3. Microgrid Based Resilience Solutions

Microgrid-based resilience solutions aim to maintain critical healthcare and WASH services during prolonged earthquake-induced outages by integrating distributed energy resources, storage, and intelligent control [33]. Compared with conventional diesel-only backup, hybrid microgrids offer improved autonomy, reduced fuel dependence, and more reliable support for essential clinical and water-related functions.

3.1. Current Practice: Grid + Diesel Backup

Most hospitals rely on grid power complemented by diesel generators designed to supply critical loads during outages. While diesel systems provide high power density and rapid response, earthquake experience shows frequent failures caused by fuel shortages, mechanical malfunction, inadequate maintenance, or damage to internal electrical networks. Field clinics typically use smaller portable generators with even more limited redundancy. These systems perform well in short outages but struggle during prolonged post-earthquake blackouts when refueling logistics are disrupted. Consequently, service continuity—especially for diagnostics, cold-chain, and WASH-supporting loads—remains vulnerable under conventional grid plus diesel configurations.

The strengths and weaknesses of this approach are summarized in Table 1, highlighting its high instantaneous power output and fast startup as strengths, but also its vulnerability to generator failure, dependence on fuel logistics, and limited autonomy for field clinics as significant weaknesses.

Table 1. Strengths and weaknesses of grid + diesel backup.

Dimension	Strengths	Weaknesses
Power capacity	High instantaneous output	Vulnerable to generator failure
Availability	Fast startup (<10 s)	Dependent on fuel supply logistics
Cost	Low capital cost	High operating cost in long outages
Reliability	Mature technology	Single-point failures common post-earthquake
Suitability for field clinics	Portable options available	Very limited autonomy

3.2. Solar PV–Battery–Diesel Configurations for Hospitals and Field Clinics

Hybrid microgrids combining solar PV, battery storage, and diesel generation provide a more resilient energy architecture for healthcare delivery. PV reduces reliance on fuel logistics, while batteries ensure stable power for sensitive clinical loads and nighttime operation. Diesel generators remain valuable as firm capacity, supporting peak demand or periods of low solar irradiance. For hospitals, appropriately sized hybrid systems can sustain critical and WASH loads for extended periods; for field clinics, modular PV–battery units significantly improve autonomy. These systems also enable intelligent dispatch, reducing diesel runtime, extending fuel reserves, and improving continuity under prolonged post-earthquake blackouts.

The comparative characteristics and roles of each component within this hybrid architecture are detailed in Table 2, which emphasizes how the integration of renewable generation and intelligent control optimizes resource use and extends system autonomy during disasters.

Table 2. Comparative characteristics of PV–battery–diesel hybrid microgrids.

Component	Role in System	Key Advantages
Solar PV	Primary renewable generation	Reduces fuel dependence; scalable
Battery storage	Stabilizes power, supports critical loads	Enables islanding, smooths variability
Diesel generator	Firm capacity, peak support	Ensures availability during low-PV periods
Controller	Manages dispatch and load prioritization	Optimizes resource use, extends autonomy

3.3. Load Prioritization and Demand Management Strategies

Effective resilience depends not only on power generation but also on managing demand through structured load prioritization. Hospitals and field clinics categorize loads into critical (life support, emergency care), high-priority (diagnostics, sterilization), WASH-supporting (pumping, disinfection), and non-critical (administrative). During outages, microgrid controllers shed lower-priority loads to preserve essential services, dynamically adjusting based on battery state of charge, PV availability, and generator capacity. Demand-side strategies—such as scheduled operation of non-critical loads, limiting HVAC zones, and optimizing water pumping cycles—significantly extend system autonomy. Such approaches transform microgrid performance from simple backup to coordinated resilience for life-saving services.

Table 3 outlines the tiered load prioritization scheme that guides this operational strategy, ensuring that life-support and emergency systems are always maintained while non-essential loads are selectively curtailed during energy scarcity.

Table 3. Tiered load prioritization scheme.

Priority Tier	Example Loads	Operational Rule
Tier 1: Critical	ICU, OR, emergency, essential ICT	Always maintained if any power available
Tier 2: High-priority	Lab, sterilization, basic imaging	Maintained unless SOC extremely low
Tier 3: WASH-support	Pumps, disinfection, wastewater	Maintained when PV or moderate SOC available
Tier 4: Non-critical	Admin areas, non-essential HVAC	Shed first during outages

4. Design of Microgrid System Under Earthquake-Induced Disruption Scenarios

To evaluate electricity-service continuity for earthquake-affected healthcare delivery, we developed a time-step, power-balance simulation model in MATLAB/Simulink for two representative facility types: a hospital and a field clinic. This framework is intended as an energy-continuity (time-step power-balance) tool for comparative resilience assessment under explicit earthquake scenarios. It does not implement optimal power-flow/advanced control optimization or transient power-quality dynamics; accordingly, results are interpreted as scenario-based continuity benchmarks supported by literature-based parameter justification and sensitivity analysis. The simulation uses a fixed time step of $\Delta t = 1$ h (consistent with the irradiance profile resolution). This choice captures day–night PV variability and energy-balance dynamics; higher-resolution (e.g., 5–15 min) power-quality transients are outside the scope of the energy-continuity model and are noted as a limitation. Each facility is modeled using tiered electrical loads reflecting operational criticality, including (i) critical clinical loads, (ii) high-priority diagnostic and support services, (iii) WASH-supporting loads (e.g., water pumping/pressure, disinfection-supporting electricity uses), and (iv) non-critical/deferrable loads. The supply portfolio comprises (a) grid electricity with scenario-defined outage and restoration profiles, (b) solar PV generation driven by hourly irradiance profiles, (c) battery energy storage with explicit state-of-charge dynamics and operating limits, and (d) diesel generation constrained by rated power, minimum loading constraints, and fuel availability under disrupted logistics. The block diagram of the designed system is shown in Figure 1.

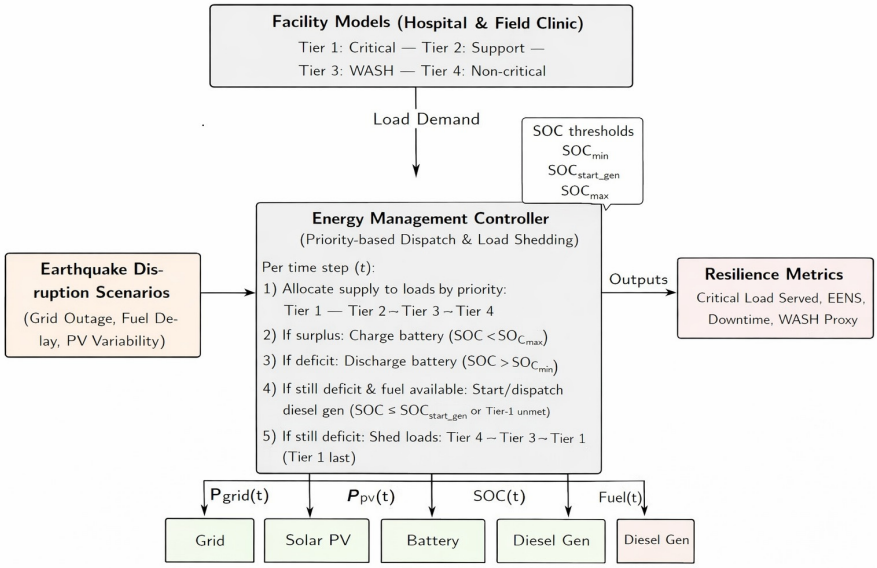


Figure 1. Block diagram of the proposed microgrid simulation framework and the priority-based energy management controller.

An energy management controller implements priority-based dispatch and load shedding. Per time step, supply is allocated to Tier 1 → Tier 4; surplus charges the battery (up to SOC_{max} = 90%), while deficits are covered by battery discharge when SOC > SOC_{min} = 20%. If Tier-1 demand remains unmet and SOC ≤ SOC_{start} = 30% (and fuel is available), the diesel generator is dispatched; remaining shortfalls are handled by shedding loads in the order Tier 4 → Tier 3 → Tier 2 (Tier 1 only if unavoidable). Under post-disaster fuel exhaustion, the controller maintains Tier-1/2 as long as feasible via PV/BESS and enforces stricter shedding of lower tiers. Under PV/BESS malfunction, the operation reverts to a diesel-only fallback mode with conservative load shedding. Upon grid restoration, the microgrid resyn-

chronizes to the main grid, prioritizes battery recharge, and gradually restores lower-tier loads. The SOC thresholds and decision sequence are summarized in Figure 1.

Figure 1 summarizes the modeling workflow. In brief, the study is implemented as a time-step energy-balance simulation in MATLAB/Simulink and proceeds as follows:

(1) Define facility types (hospital and field clinic) and assign tiered demand profiles (Tier 1–4);
(2) Define supply components (grid availability profile, PV generation profile, battery model with SOC limits, and diesel generator with fuel constraints);
(3) Encode earthquake disruption scenarios as time-varying constraints (grid outage duration/restoration, fuel availability/refueling delays, and PV variability);
(4) Execute the per-time-step energy management controller (priority dispatch, battery charge/discharge, diesel dispatch, and tiered load shedding);
(5) Run simulations for all scenarios and configurations (diesel-only baseline vs. hybrid PV–battery–diesel options);
(6) Compute outputs/metrics, including critical-load served fraction, critical service downtime by tier, EENS, diesel runtime/fuel consumption, SOC trajectories, and the WASH-supportability proxy.

The detailed operational logic of the energy management controller, as represented in the simulation framework, is executed through a hierarchical, priority-based dispatch sequence at each hourly time step (t). The decision-making process begins by calculating the total available non-dispatchable power (P_{avail}), which is the sum of photovoltaic generation (P_{PV}) and grid supply (P_{Grid}). This available power is first allocated to the four load tiers in descending order of criticality: Tier 1 (Critical Clinical), Tier 2 (Support), Tier 3 (WASH), and Tier 4 (Non-critical).

In scenarios where P_{avail} exceeds the total load demand, the surplus energy is directed to charge the battery storage system, provided the state-of-charge (SOC) is below the maximum threshold (SOC_{max} = 90%). Conversely, if a power deficit occurs ($P_{avail} < \sum Loads$), the controller initiates a discharge sequence from the battery to cover the shortfall, following the same priority order (Tier 1 to Tier 4), as long as the battery remains above the deep-discharge protection limit (SOC_{min} = 20%).

To ensure the continuity of the most essential services during prolonged outages or low-solar periods, an emergency backup protocol is triggered if Tier 1 demand remains unmet and the battery SOC drops to or below the dispatch threshold (SOC_{start}=30%). Under these conditions, and assuming fuel is available, the diesel generator is started to supply Tier 1 and Tier 2 loads, with any excess generator capacity used to recharge the battery up to SOC_{max}. If the combined supply from all sources (PV, Grid, Battery, and Diesel) is still insufficient to meet the total demand, the controller enforces a tiered load-shedding sequence, disconnecting loads starting from Tier 4, then Tier 3, and finally Tier 2, to preserve Tier 1 clinical functions as the absolute priority. This structured operational logic ensures that critical healthcare and WASH services are maintained for the maximum possible duration under resource constraints.

At each simulation time step, available supply is allocated sequentially to higher-tier loads; when supply is insufficient, lower-tier loads are curtailed according to predefined prioritization rules. This operational representation enables a direct mapping between infrastructure-level disruptions and service-level performance. Specifically, earthquake damage is represented at the infrastructure layer through grid unavailability and limitations in on-site backup (e.g., generator derating or failure, delayed refueling, and reduced effective capacity due to internal distribution constraints). These constraints propagate to the facility/service layer as reduced ability to sustain essential clinical operations (e.g., emergency care, surgery, ICU, obstetric/neonatal services, dialysis), diminished infec-

tion prevention and control (IPC) capacity via WASH- and sterilization-related electricity needs, and degraded information/communication functions required for triage, referral, and coordination. Ultimately, these service degradations create population-level public health risks, including avoidable mortality, complications from delayed or interrupted treatment (including chronic disease management), and increased infectious disease risk in the post-earthquake setting.

System performance is quantified using health-service continuity metrics that are computable within the energy-balance framework, including the fraction of critical load served, service downtime (hours of interruption) by load tier, expected energy not served (EENS), diesel runtime and fuel consumption, battery state-of-charge trajectories, and WASH-supportability proxies (e.g., ability to sustain minimum electricity for water and hygiene-supporting functions). This integrated design links the public health mechanisms discussed previously to microgrid configuration choices (grid + diesel baseline versus PV–battery–diesel variants) and to operational strategies (load prioritization and demand management), enabling systematic comparison of resilience gains across earthquake-induced disruption scenarios.

4.1. System Description and Assumptions

The simulation represents two facilities: a 200-bed hospital with 150 kW peak critical load and a 20-bed field clinic with 15 kW peak critical load. Facility sizes are intended as representative 'order-of-magnitude' archetypes for scenario comparison rather than site-specific designs. Because bed count, electrification level, and critical-load fraction vary across LMIC/HIC contexts, results should be interpreted as comparative (relative) resilience gains under consistent assumptions rather than universal absolute values. PV capacity is sized to cover daytime critical loads under typical irradiance; battery storage provides 4–6 h of critical-load autonomy; diesel generators supply firm backup. PV capacity was selected using a design rule (targeting ~60–80% coverage of daytime critical-load demand under typical irradiance) to reduce diesel dependence; formal sizing optimization was not performed and is identified as a future extension. Grid power is assumed unavailable during the earthquake-induced blackout period. PV generation follows a normalized hourly profile (winter/typical conditions). Battery efficiency is 90% (round-trip); diesel fuel consumption is 0.25 L/kWh. Load profiles include diurnal variation with peak demand during daytime clinical hours. Diesel fuel use is modeled with a simplified linear rate (0.25 L/kWh). Real generators exhibit nonlinear efficiency, minimum loading, and no-load consumption; therefore, runtime and fuel autonomy estimates may be optimistic. This is treated as a modeling limitation and partially addressed via sensitivity bounds on fuel-rate. Load profiles were constructed using published benchmark ranges and engineering assumptions rather than site-specific monitoring data. To improve transparency, we report the peak-to-base ratios, tier allocations, and a sensitivity analysis showing how critical-load served changes with $\pm 20\%$ variations in (i) critical-load magnitude, (ii) PV capacity factor, and (iii) battery usable capacity. This limitation is discussed explicitly as a constraint on external validity. WASH loads are modeled as intermittent pumping cycles totaling 10–15% of critical load energy. The load shedding algorithm prioritizes critical clinical loads first, followed by high-priority diagnostic and support services, then WASH-supporting functions, and finally non-critical or deferrable loads. For example, life-support equipment and emergency care systems are maintained as long as possible, while non-essential lighting and administrative loads are curtailed during supply shortages. The specific technical specifications and modeling assumptions for both facilities are summarized in Table 4, which provides the quantitative basis for the comparative performance analysis across the different disaster scenarios.

Table 4. System parameters and assumptions.

Parameter	Hospital	Field Clinic	Notes
Peak critical load (kW)	150	15	Life-support, emergency, OR, essential ICT
PV capacity (kW)	100	20	Sized for daytime critical load coverage
Battery capacity (kWh)	600	90	4–6 h autonomy at critical load
Diesel generator (kW)	200	25	Firm backup capacity
Diesel fuel (L)	Variable by scenario	Variable	Fuel scarcity modeled in S2–S5
Battery efficiency (%)	90	90	Round-trip
Diesel fuel rate (L/kWh)	0.25	0.25	Typical for medium generators
WASH load (% of critical)	12	10	Pumping, disinfection cycles

Due to limited access to post-earthquake facility monitoring datasets, full empirical validation is outside the scope of this study. To strengthen credibility, we (i) justify all key parameters using the literature-based ranges (load magnitudes, PV yield/irradiance profiles, diesel fuel-rate assumptions, and battery usable capacity), and (ii) report a sensitivity analysis over the main parameters, quantifying impacts on critical-load served and critical-service downtime. These results are interpreted as robustness checks rather than a substitute for field validation. Robustness was assessed via one-at-a-time sensitivity tests ($\pm$20%) on PV output, battery capacity, critical-load level, and diesel fuel-rate; the qualitative ranking of architectures remains unchanged under these ranges. Sensitivity analysis was added to address parameter ambiguity, and qualitative ranking (hybrid > diesel only under fuel constraints) was reported to be robust across the tested ranges.

4.2. Scenario Design (Earthquake-Induced Outage Cases)

Five scenarios simulate earthquake-induced blackouts with varying duration, fuel availability, and PV conditions. S1 (baseline): 72 h blackout, unlimited diesel fuel, typical PV—tests conventional backup adequacy. S2: 72 h blackout, fuel available only for first 24 h—simulates fuel supply disruption. S3: 72 h blackout, 48 h fuel, low PV (winter/cloudy)—compound stress. S4: 168 h (7-day) blackout, 72 h fuel, typical PV—prolonged outage. S5: 168 h blackout, no diesel fuel, typical PV—tests PV–battery-only resilience. Each scenario runs for both hospital and field clinic, comparing three microgrid architectures: diesel-only, PV + battery + grid, and PV + battery + diesel hybrid. A window of 72 h was used to represent the acute response period, during which access, refueling, and repairs are typically restricted, while 168 h was used to represent early recovery. Seasonal and weekday/weekend variability were not explicitly modeled; therefore, results reflect typical profile conditions and should be interpreted comparatively.

4.3. Performance Metrics: Health Service Continuity and Safe Water Provision

Performance is evaluated using four primary metrics aligned with health-service continuity objectives. The critical-load served fraction (%) quantifies the proportion of critical clinical load demand successfully met over the outage period, serving as a direct proxy for essential service availability. Critical service downtime (hours) measures the cumulative duration during which critical loads cannot be fully supplied, indicating the length of service interruptions. Expected Energy Not Served (EENS) for critical loads (kWh) aggregates unmet demand and serves as a standard reliability indicator. The WASH-supportability proxy assesses whether minimum safe-water-support loads can be maintained, linking energy performance to conditions necessary for infection prevention.

The WASH-supportability proxy is mathematically defined in Equation (1) as the percentage of total simulation time steps during which the power supplied to Tier 3 loads meets or exceeds the minimum required threshold $P_{washmin}$:

$$\text{Supportability} = \frac{\sum_{t=1}^{T} \text{Number of time steps where}(P_{WASH,t} \geq P_{washmin})}{T} \times 100\% \quad (1)$$

In Equation (1), T represents the total number of time steps and $P_{WASH,t}$ is the power delivered to WASH loads at time t. Intermittent pumping is represented by the time-varying demand profile $P_{WASH,t}$ within the simulation.

Collectively, these metrics translate engineering outputs into health-relevant continuity indicators, as summarized in Table 5. These engineering outputs are interpreted through health-service continuity proxies, linking electricity shortfalls (by tier and duration) to the ability to sustain essential clinical functions and minimum WASH conditions for infection prevention, rather than to direct clinical/epidemiological outcomes.

Table 5. Performance metrics definitions.

Metric	Definition	Health-Service Interpretation
Critical-load served (%)	(Energy delivered to critical loads/Energy demanded) × 100	Direct measure of essential clinical service continuity
Critical service downtime (h)	Total hours critical loads not fully supplied	Duration of service interruption
EENS for critical loads (kWh)	Σ (Demand − Supply) over outage period	Cumulative unmet essential energy demand
WASH-supportability proxy	Feasibility of meeting minimum safe-water load over time	Proxy for infection prevention capacity
Diesel runtime (h)	Total generator operating hours	Fuel consumption and logistics burden

4.4. Sensitivity and Robustness Analysis

To evaluate the robustness of the simulation results and quantify the impact of parameter uncertainties, a one-at-a-time sensitivity analysis was conducted. The analysis focused on five primary technical and operational parameters: (i) PV capacity factor, (ii) battery usable capacity, (iii) critical-load magnitude, (iv) diesel fuel consumption rate, and (v) the minimum WASH power threshold ($P_{wash_{min}}$). Each parameter was perturbed by ±20% relative to its baseline value, except for the WASH-load fraction, which was varied between 5% and 15% of the peak critical load. The sensitivity of the system performance was assessed using three key metrics: critical-load served (%), expected energy not served (EENS), and critical service downtime. The numerical findings of these sensitivity tests are presented and discussed in Section 5 (Table 6), providing a comprehensive overview of the model's stability across diverse operational conditions.

Table 6. Sensitivity of resilience metrics to ±20% parameter variations (Hybrid Microgrid—S2).

Parameter Variation	Critical-Load Served (%)	Critical Service Downtime (h)	EENS (kWh)
Baseline (Hybrid—S2)	87.0%	10.0	155
PV Capacity Factor (+20%)	91.2%	7.5	112
PV Capacity Factor (−20%)	81.5%	14.0	210
Battery Capacity (+20%)	89.5%	8.5	135
Battery Capacity (−20%)	83.2%	12.5	188
Critical Load (+20%)	82.1%	13.5	205
Critical Load (−20%)	92.4%	6.5	95
Diesel Fuel-Rate (+20%)	86.8%	10.5	158
Diesel Fuel-Rate (−20%)	87.2%	9.5	152

5. Simulation Results and Comparative Analysis

The simulation results reveal significant disparities in health-service continuity depending on the microgrid architecture and the severity of the earthquake-induced disruption. As can be seen in Figure 2, under Scenario 1 (S1: 72 h, unlimited fuel), all configurations maintain a critical-load served fraction above 95% for both the hospital and the field clinic. This confirms that conventional backup systems are adequate as long as fuel logistics remain uninterrupted, with hybrid systems providing marginal gains through daytime solar contributions. A window of 72 h was used to represent the acute response period, during which access, refueling, and repairs are typically restricted, while 168 h was used to rep-resent early recovery. Seasonal and weekday/weekend variability were not explicitly modeled; therefore, results reflect typical profile conditions and should be interpreted comparatively.

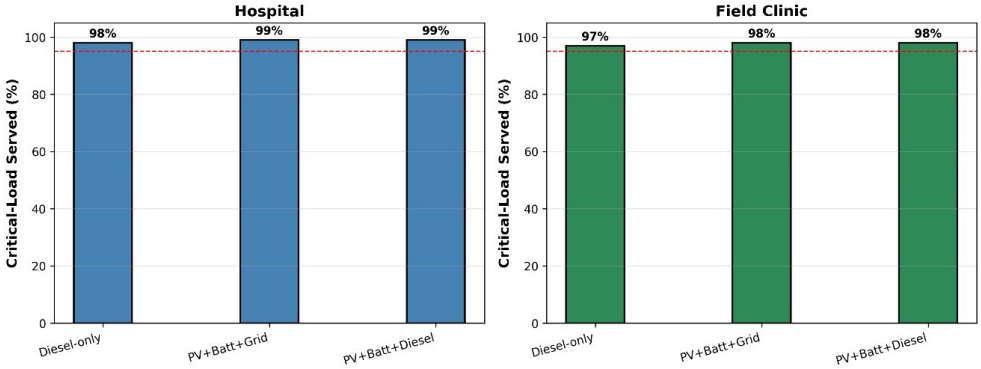


Figure 2. Critical-load served fraction—S1 (72 h, unlimited fuel).

In this baseline scenario, the numerical results show that all systems achieve near-perfect continuity, with critical load fulfillment staying above 0.95. The hybrid system slightly reduces the reliance on the grid and diesel during daylight hours, but the overall performance difference remains minimal due to the constant availability of fuel.

As illustrated in Figure 3, Scenario 2 (S2: 72 h, 24 h fuel) demonstrates that fuel supply disruptions severely degrade the performance of diesel-only systems. In this case, diesel-only configurations experience critical service downtime ranging from 38 to 42 h for hospitals and 40 to 45 h for field clinics, causing the critical-load served fraction to plummet to 45–50%. Conversely, hybrid microgrids leverage PV and battery storage to maintain 85–90% of critical services, effectively bridging the gap created by fuel exhaustion.

The data indicates that hybrid systems reduce critical downtime by approximately 70–75% compared to diesel-only setups when fuel is limited to 24 h. Numerically, the hybrid configuration maintains a service fraction of 0.85–0.90, nearly doubling the critical-load served fraction of the healthcare facility during the first three days of the disaster.

As shown in Figure 4, Scenario 3 (S3: 72 h, 48 h fuel, low PV) introduces compound stress, where both fuel scarcity and low solar irradiance challenge the system. Even under these unfavorable conditions, hybrid configurations outperform diesel-only systems by 25–30 percentage points, sustaining 70–75% of critical loads compared to the 40–45% achieved by traditional backup generators.

Despite the reduction in solar yield, the hybrid system still provides a significant resilience buffer, maintaining critical services at a 0.70–0.75 fraction. This highlights that even a sub-optimal renewable resource is superior to a total reliance on depleted fuel reserves, which leads to a 55% failure rate in clinical loads.

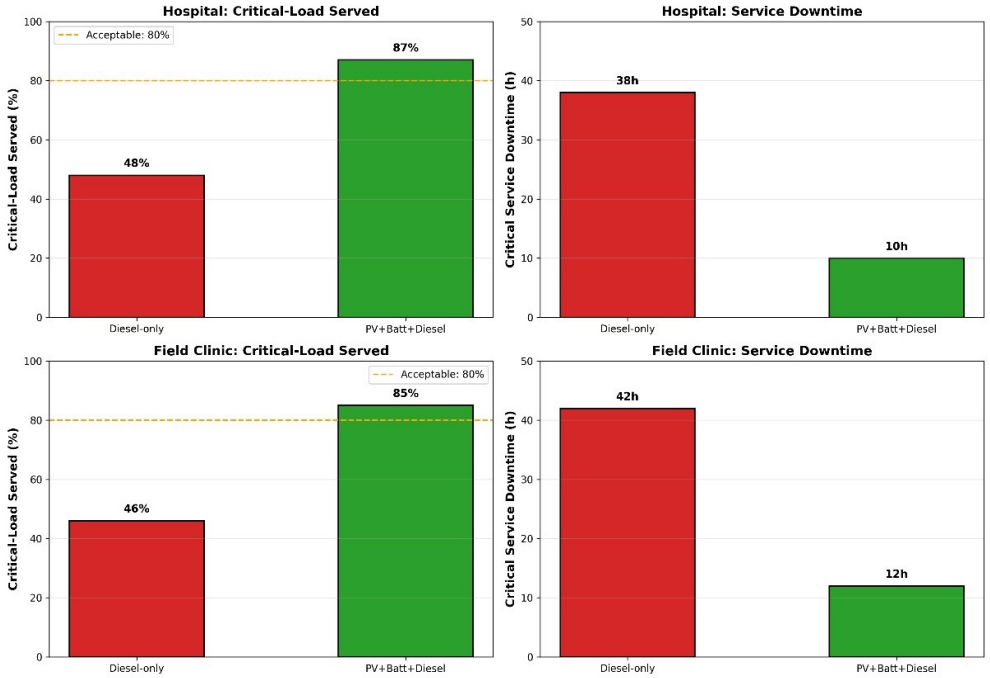


Figure 3. Performance comparison—S2 (72 h, 24 h fuel).

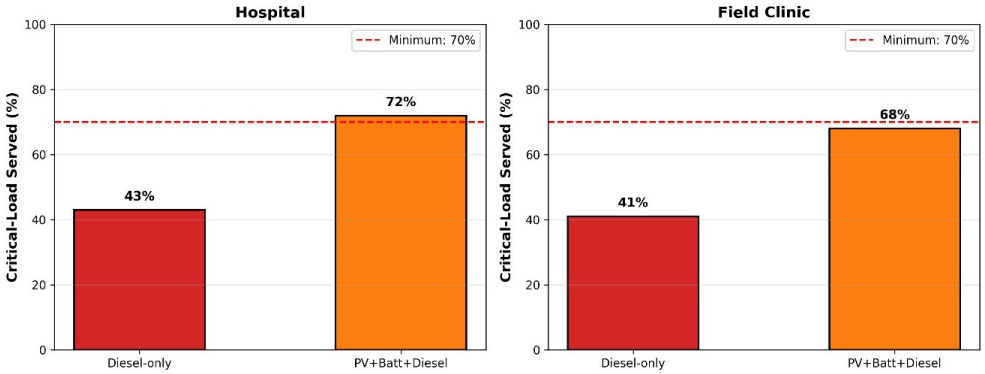


Figure 4. Critical-load served—S3 (72 h, 48 h fuel, low PV).

As can be observed in Figure 5, during prolonged outages (S4: 168 h, 72 h fuel), diesel-only systems completely collapse after the third day when fuel is depleted. In contrast, hybrid microgrids demonstrate superior long-term resilience by sustaining 75–80% of critical loads throughout the entire week through continuous PV–battery cycling, ensuring that the facility remains functional during the extended recovery phase.

The time-series data shows a total service collapse for diesel systems at the 72 h mark, whereas the hybrid system maintains a steady oscillation of 75–80% service continuity. This numerical trend proves that hybridization is essential for disasters where infrastructure repair and fuel logistics are expected to take more than three days.

As demonstrated in Figure 6, Scenario 5 (S5: 168 h, no diesel) evaluates the potential of PV–battery-only systems, which can maintain 60–70% of critical services under typical irradiance. While these systems offer a viable alternative when fuel logistics are entirely non-functional, the results indicate that they are highly sensitive to weather variability, making the hybrid PV + battery + diesel configuration the most reliable choice for guaranteed continuity. The results show that without any diesel support, a renewable-only system still manages to serve 65% of hospital critical loads, though this drops during low-sunlight periods. The bottom panel of the figure confirms that across all tested scenarios, the hybrid

architecture consistently yields the lowest Expected Energy Not Served (EENS) and the highest service reliability.

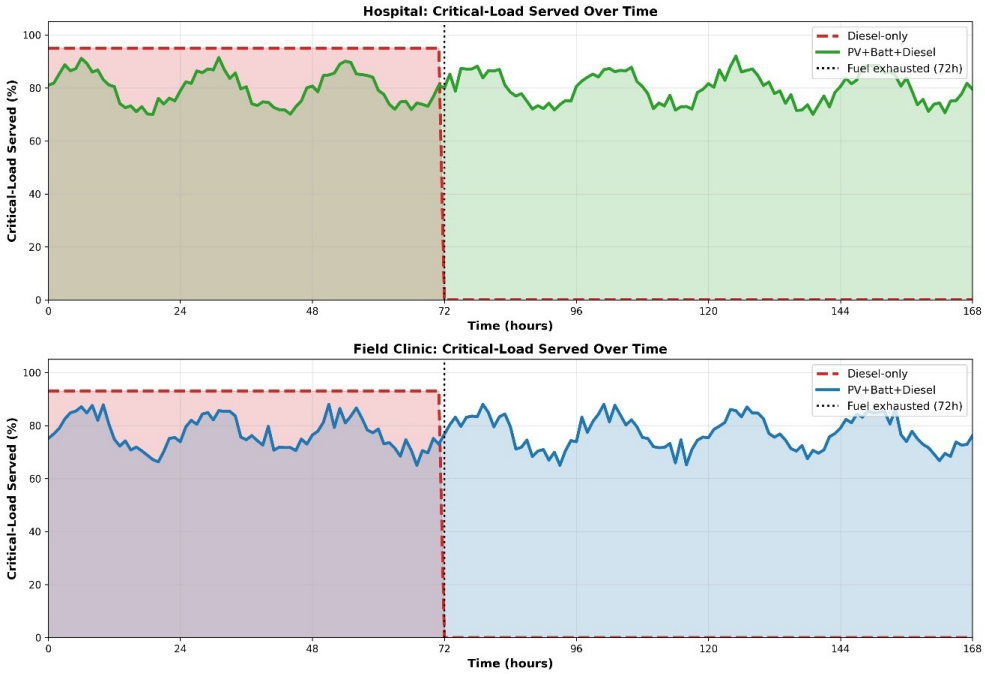


Figure 5. Time-series performance—S4 (168 h, 72 h fuel).

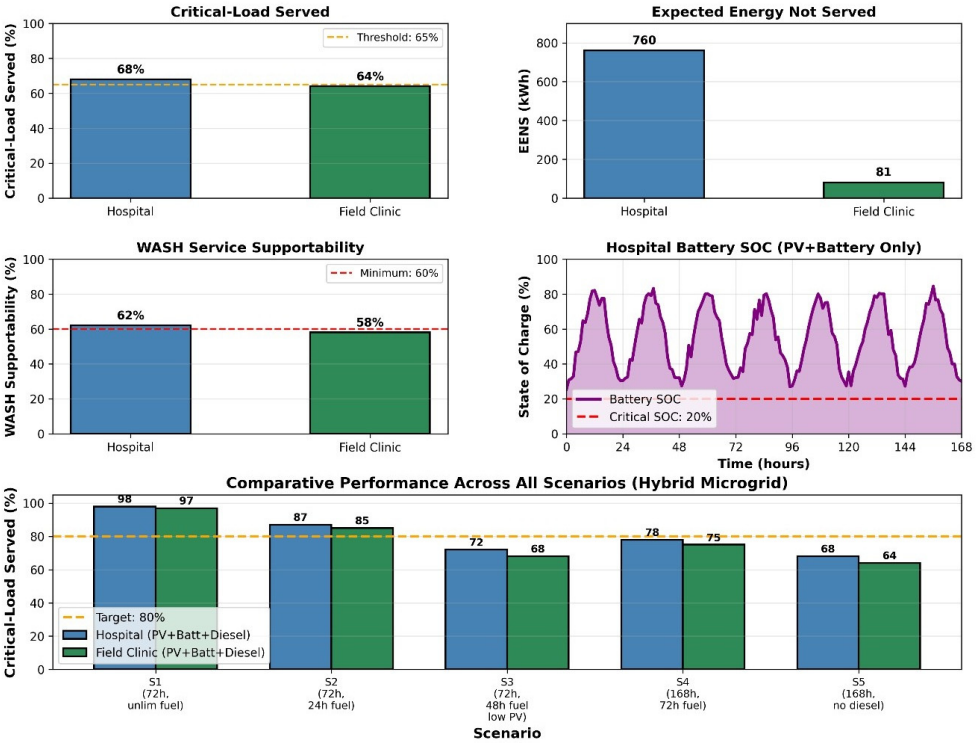


Figure 6. PV + Battery performance and cross-scenario summary—S5 (168 h, no diesel).

The collective analysis of the simulation data confirms that earthquake resilience in healthcare is fundamentally tied to energy diversity. While traditional diesel systems are sufficient for short-term, fuel-secure events, they fail catastrophically during the logistical disruptions typical of major seismic events. Hybrid microgrids not only reduce diesel runtime by 50–60%, thereby extending limited fuel reserves, but also ensure that critical

WASH and clinical services remain operational even when the external supply chain breaks down. Ultimately, the integration of PV and battery storage acts as a critical-service redundancy associated with an improved ability to sustain essential care; this maintains two to four times higher service continuity compared to conventional backup systems in fuel-constrained disaster environments. Although the initial capital investment for hybrid microgrid systems may be higher than conventional diesel backups, the reduction in critical service downtime and associated health impacts, combined with lower operational fuel costs, suggest a favorable cost–benefit balance. Future work should include detailed economic analyses incorporating the value of lost load and health outcome improvements to support policy and investment decisions. Sensitivity results indicate that critical-load magnitude, PV yield (capacity factor), and battery usable capacity are the dominant drivers of critical-load served and downtime, while fuel-rate assumptions primarily affect diesel runtime and autonomy.

Effective implementation of these systems requires specific design strategies tailored to the unique demands of earthquake-prone regions. PV capacity should be sized to cover 60–80% of daytime critical-load demand to minimize diesel dependency, while battery storage should provide 4–6 h of autonomy to bridge overnight periods and facilitate load shifting. Although diesel generators remain essential for firm backup, sizing them for 50–60% of peak load—rather than full capacity—optimizes fuel reserve requirements without compromising safety. Furthermore, automated controllers must enforce load prioritization to ensure that essential clinical and WASH services are served first. To further mitigate logistical risks, on-site fuel storage should be maintained for 30–45 days, and system designs must account for low-irradiance conditions through conservative PV sizing and adequate battery capacity to ensure year-round health-service continuity.

Across S1–S5, the dominant driver of critical-service continuity is the interaction between (i) outage duration/restoration timing, (ii) fuel availability constraints, and (iii) PV–battery sizing and SOC limits. Apparent differences across figures arise because some scenarios are energy-limited (fuel exhaustion dominates) while others are power-limited (instantaneous capacity and tiering dominate). From a planning perspective, the results suggest (a) prioritizing PV–BESS to reduce diesel runtime and protect Tier-1/2 loads under fuel disruption, (b) using tier definitions and load-shedding rules as an explicit design input (not an afterthought), and (c) treating fuel logistics (delay/availability) as a first-class scenario parameter when specifying backup requirements for seismic regions.

To further validate the reliability of the simulation findings, a quantitative sensitivity analysis was performed on the hybrid microgrid configuration under Scenario 2 (72 h outage, 24 h fuel). Table 6 summarizes the impact of ±20% variations in key technical parameters on the primary resilience metrics. The results indicate that while battery capacity and PV yield are the most influential drivers of performance, the hybrid architecture consistently maintains a critical-load served fraction above 80% across all tested ranges. This confirms that the performance advantages of the proposed hybrid solution remain robust even under significant parameter uncertainty.

6. Conclusions

This study demonstrates that hybrid PV–battery–diesel microgrids significantly enhance health-service continuity in earthquake-affected hospitals and field clinics compared to conventional diesel-only backup systems. Simulation results across five outage scenarios indicate that renewable-integrated systems reduce critical-service downtime by 70–75% and maintain safe-water support capacity under fuel-constrained conditions. These findings have important implications for disaster risk reduction policies, health system resilience planning, and microgrid design standards in seismic regions.

Health facilities represent critical infrastructure for effective earthquake response and recovery. Conventional diesel backup systems rely on the assumption of reliable fuel supply, an assumption that often fails during supply chain disruptions caused by disasters. This study quantifies the vulnerability of diesel-only systems, which lose 50–55% of critical-load capacity within 24 to 72 h following fuel exhaustion. Hybrid microgrids mitigate this risk by diversifying energy sources, reducing fuel dependency by 50–60%, and enabling autonomous operation during logistical disruptions. From a disaster risk reduction perspective, these improvements translate into reduced critical-service downtime, which is associated with an improved ability to sustain essential care; however, direct health outcomes were not quantified here and would require dedicated epidemiological modeling. Consequently, health system planners should prioritize renewable-integrated backup solutions for all critical facilities in seismic zones, supported by national standards and financing mechanisms. Limitations include benchmark-based (non-site-specific) load profiles, simplified diesel fuel modeling, hourly time-step resolution, and the use of continuity proxies (rather than clinical/epidemiological outcome models). Future work will incorporate validation datasets, uncertainty analysis, and extended operational/optimization formulations.

This study employed simplified load profiles and proxy metrics for WASH supportability due to limited availability of real hospital data. Future research should focus on validating simulation outputs against data from earthquake-affected facilities and incorporating detailed WASH load modeling and water quality monitoring. Further work is also needed to extend the analysis to multi-facility microgrids and district-level resilience, evaluate economic trade-offs and financing mechanisms, assess climate variability impacts on PV performance in different seismic regions, and develop operational protocols for load shedding and fuel rationing during extended outages. Collaboration with health facilities, utilities, and disaster management agencies will be essential to translate these findings into effective policy and practice.

Author Contributions: Conceptualization, S.E.E. and A.Ö.E.; methodology, A.Ö.E.; software, S.E.E.; validation, S.E.E. and A.Ö.E.; formal analysis, S.E.E. and A.Ö.E.; investigation, S.E.E.; resources, A.Ö.E.; data curation, S.E.E.; writing—original draft preparation, S.E.E.; writing—review and editing, A.Ö.E.; visualization, S.E.E.; supervision, A.Ö.E. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author(s).

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Pearson, L.; Pelling, M. The UN Sendai framework for disaster risk reduction 2015–2030: Negotiation process and prospects for science and practice. *J. Extrem. Events* **2015**, *2*, 1571001. [CrossRef]
2. Rinaldi, S.M.; Peerenboom, J.P.; Kelly, T.K. Identifying, understanding, and analyzing critical infrastructure interdependencies. *IEEE Control Syst. Mag.* **2001**, *21*, 11–25.
3. Ouyang, M. Review on modeling and simulation of interdependent critical infrastructure systems. *Reliab. Eng. Syst. Saf.* **2014**, *121*, 43–60. [CrossRef]
4. Ventura, C.; Chiacchio, F.; D'Urso, D.; Tina, G.M.; Castillo, G.J.; Oliveri, L.M. An AHP-based multicriteria framework for evaluating renewable energy service proposals in public healthcare infrastructure: A case study of an Italian hospital. *Energies* **2025**, *18*, 4680. [CrossRef]

5. Panteli, M.; Mancarella, P. The grid: Stronger, bigger, smarter?: Presenting a conceptual framework of power system resilience. *IEEE Power Energy Mag.* **2015**, *13*, 58–66. [CrossRef]
6. Sapkota, A.; Karki, R. Resilience investment against extreme weather events considering critical load points in an active microgrid. *Appl. Sci.* **2025**, *15*, 6973. [CrossRef]
7. Suanpang, P.; Jamjuntr, P. Machine learning models for solar power generation forecasting in microgrid application: Implications for smart cities. *Sustainability* **2024**, *16*, 6087. [CrossRef]
8. Souza Junior, M.E.T.; Freitas, L.C.G. Power electronics for modern sustainable power systems: Distributed generation, microgrids and smart grids—A review. *Sustainability* **2022**, *14*, 3597. [CrossRef]
9. Altin, N.; Eyimaya, S.E.; Nasiri, A. Multi-agent-based controller for microgrids: An overview and case study. *Energies* **2023**, *16*, 2445. [CrossRef]
10. Ulbig, A.; Borsche, T.S.; Andersson, G. Impact of low rotational inertia on power system stability and operation. *IFAC Proc.* **2014**, *47*, 7290–7297. [CrossRef]
11. Klinger, C.; Landeg, O.; Murray, V. Power outages, extreme events and health: A systematic review of the literature from 2011–2012. *PLoS Curr.* **2014**. [CrossRef]
12. Marqusee, J.; Don, D.J., II. Reliability of emergency and standby diesel generators: Impact on energy resiliency solutions. *Appl. Energy* **2020**, *268*, 114918. [CrossRef]
13. Bata, M.T.H.; Carriveau, R.; Ting, D.S.K. Urban water supply systems' resilience under earthquake scenario. *Sci. Rep.* **2022**, *12*, 20555. [CrossRef]
14. Hervás-Zaragoza, J.; Colmenar-Santos, A.; Rosales-Asensio, E.; Colmenar-Fernández, L. Microgrids as a mechanism for improving energy resilience during grid outages: A post COVID-19 case study for hospitals. *Renew Energy* **2022**, *199*, 308–319. [CrossRef]
15. Billanes, J.D.; Jørgensen, B.N.; Ma, Z. A framework for resilient community microgrids: Review of operational strategies and performance metrics. *Energies* **2025**, *18*, 405. [CrossRef]
16. Ali, M.; Vasquez, J.C.; Guerrero, J.M.; Guan, Y.; Golestan, S.; De La Cruz, J.; Khan, B. A comparison of grid-connected local hospital loads with typical backup systems and renewable energy system based ad hoc microgrids for enhancing the resilience of the system. *Energies* **2023**, *16*, 1918. [CrossRef]
17. Achour, N.; Miyajima, M. Post-earthquake hospital functionality evaluation: The case of Kumamoto Earthquake 2016. *Earthq. Spectra* **2020**, *36*, 1670–1694.
18. Lee, C.W.; Kwon, H.J.; Yoo, D.G. Seismic reliability assessment of water supply systems considering critical paths. *Appl. Sci.* **2020**, *10*, 8056. [CrossRef]
19. Lagrange, A.; de Simón-Martín, M.; González-Martínez, A.; Bracco, S.; Rosales-Asensio, E. Sustainable microgrids with energy storage as a means to increase power resilience in critical facilities: An application to a hospital. *Int. J. Electr. Power Energy Syst.* **2020**, *119*, 105865. [CrossRef]
20. Masrur, H.; Sharifi, A.; Islam, M.R.; Hossain, M.A.; Senjyu, T. Optimal and economic operation of microgrids to leverage resilience benefits during grid outages. *Int. J. Electr. Power Energy Syst.* **2021**, *132*, 107137. [CrossRef]
21. World Health Organization. *WASH in Health Care Facilities: Global Baseline Report 2019*; World Health Organization: Geneva, Switzerland, 2019.
22. World Health Organization. *WHO Water, Sanitation and Hygiene Strategy 2018–2025 (No. WHO/CED/PHE/WSH/18.03)*; World Health Organization: Geneva, Switzerland, 2018.
23. Adhikari, B.; Mishra, S.R.; Marahatta, S.B.; Kaehler, N.; Paudel, K.; Adhikari, J.; Raut, S. Earthquakes, fuel crisis, power outages, and health care in Nepal: Implications for the future. *Disaster Med. Public Health Prep.* **2017**, *11*, 625–632. [CrossRef]
24. Taherkhani, A.H.; Heravi, G.; AminShokravi, A. Developing a framework to enhance the seismic resilience of the electricity distribution system feeding the healthcare system. *Int. J. Disaster Risk Reduct.* **2022**, *71*, 102801. [CrossRef]
25. Amini, F.; Ghassemzadeh, S.; Rostami, N.; Tabar, V.S. A stochastic two-stage microgrid formation strategy for enhancing distribution network resilience against earthquake event incorporating distributed energy resources, parking lots and responsive loads. *Sustain. Cities Soc.* **2024**, *101*, 105191. [CrossRef]
26. Najafi, J.; Peiravi, A.; Anvari-Moghaddam, A. Enhancing integrated power and water distribution networks seismic resilience leveraging microgrids. *Sustainability* **2020**, *12*, 2167. [CrossRef]
27. Cheng, B.; Nozick, L.; Dobson, I. Investment planning for earthquake-resilient electric power systems considering cascading outages. *Earthq. Spectra* **2022**, *38*, 1734–1760. [CrossRef]
28. Zhao, J.; Ding, F.; Wang, Z.; Ren, J.; Zhao, J.; Wang, Y.; Li, Q. A rapid public health needs assessment framework for after major earthquakes using high-resolution satellite imagery. *Int. J. Environ. Res. Public Health* **2018**, *15*, 1111. [CrossRef]
29. Christiansen, N.; Kaltschmitt, M.; Dzukowski, F. Electrical energy consumption and utilization time analysis of hospital departments and large scale medical equipment. *Energy Build.* **2016**, *131*, 172–183. [CrossRef]
30. Zhai, C.; Yu, P.; Wen, W. A physical-organizational method for the functionality assessment of a hospital subjected to earthquakes. *J. Earthq. Eng.* **2022**, *26*, 7119–7139. [CrossRef]

31. Rezvykh, A.D.; Ovcharenko, A.P.; Lemeshkin, R.N.; Kovalchuk, S.V. Modeling the workflow of a field hospital in earthquake conditions. *Procedia Comput. Sci.* **2022**, *212*, 330–339. [CrossRef]
32. Adachi, T.; Ellingwood, B.R. Serviceability of earthquake-damaged water systems: Effects of electrical power availability and power backup systems on system vulnerability. *Reliab. Eng. Syst. Saf.* **2008**, *93*, 78–88. [CrossRef]
33. Hirose, K.; Reilly, J.; Irie, H. The Sendai microgrid operational experience in the aftermath of the Tohoku earthquake: A case study. *New Energy Ind. Technol. Dev. Organ.* **2013**, *308*, 1–6.

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.