

Flood-Adaptive Primary Care Clinics with Smart Microgrids and Rapid-Deploy MedTech [†]

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Abstract

Extreme hydro-meteorological events are intensifying under climate change, disproportionately disrupting last-mile healthcare in flood-prone geographies. In this study, flood-adaptive primary care clinics (FAPCCs) integrated with islandable smart microgrids and a rapid-deploy medical technology stack (MedTech) are developed and evaluated to ensure continuity of essential services (triage, maternal and child health, vaccination cold-chain, minor procedures, diagnostics, and telemedicine) during fluvial, pluvial, and coastal flooding. Evidence on resilient health facilities, microgrid architectures, distributed energy resources, and modular clinical systems is presented in a multi-layer systems design: (1) a modular, amphibious, and elevatable clinic chassis; (2) a photovoltaic–battery–diesel hybrid system with demand-aware energy management; (3) redundant connectivity long-term evolution/fifth-generation, satellite, and very high frequency; (4) a rapid-deploy MedTech kit including point-of-care diagnostics, low-temperature cold-chain, negative-pressure isolation, and sterilization modules; and (5) flood-aware logistics using unmanned aerial vehicle/unmanned surface vehicle. A mixed-integer linear programming sizing is formulated and dispatched with a continuity-of-care reliability metric that couples energy availability to clinical throughput. Simulation across three archetypal sites (peri-urban delta, inland riverine, coastal estuary) shows that FAPCCs achieve the service availability of higher than 99.5% across 7-day grid outage scenarios while reducing fuel use by 62–81% relative to diesel-only baselines, maintaining vaccine temperatures within 2–8 °C with <0.1% thermal excursion time, and sustaining telemedicine quality of service with <150 ms median uplink latency in hybrid networks. A life-cycle cost analysis indicates a 7.1–9.8 year discounted payback from fuel displacement and avoided service loss. Deployment playbooks and policy guidance are also proposed for Ministries of Health and Disaster Agencies in monsoon-impacted regions.



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1. Introduction

Floods are the most prevalent natural hazard globally, with escalating frequency and intensity under anthropogenic climate change. According to the World Meteorological Organization and the United Nations Office for Disaster Risk Reduction, over two billion people were directly affected by flood events between 2000 and 2020, with Southeast Asia

and sub-Saharan Africa experiencing the highest levels of mortality and displacement [1–4]. Floods destroy infrastructure and trigger cascading impacts on health systems: waterborne diseases, injuries, disruption of chronic disease management, and psychological trauma. Primary healthcare, responsible for first-contact, continuous, and comprehensive services, faces the greatest vulnerability due to its dependency on reliable electricity, medical cold chains, and logistics [1,3].

The care industry forms the backbone of community-level health resilience, providing essential services including triage, antenatal and postnatal care, maternal- and child health, minor surgical procedures, vaccination programs, and chronic disease follow-up [5,6]. During floods, demand for these services increases dramatically. Yet clinics in flood-prone regions are often housed in non-resilient structures, relying on fragile grid connections, diesel generators subject to fuel scarcity, and road-based resupply chains that are quickly cut off [7,8]. As a result, clinics face service disruption precisely when continuity is most critical.

To address these vulnerabilities, the concept of flood-adaptive primary care clinics (FAPCCs) is introduced in this study with mobile, modular, and flood-ready healthcare nodes integrated with smart microgrids and rapid-deploy medical technology for the following.

- Energy resilience: Smart, islandable microgrids combining photovoltaics (PV), battery energy storage systems (BESS), and diesel backup enable reliable power autonomy for at least 7–10 days of grid outages [5,9].
- Clinical continuity: A tiered load design prioritizes vaccine cold-chains, emergency lighting, sterilization, and diagnostic equipment, with scalable modules for surge capacity [10–12].
- Flood-adaptive infrastructure: Amphibious chassis, elevatable decks, and pontoons reduce submersion risk, while unmanned aerial vehicle/unmanned surface vehicle (UAV/USV) logistics mitigate road inaccessibility [13–16].
- Digital health integration: Telemedicine and health information systems, enabled by long-term evolution/fifth-generation, satellite, and very high frequency hybrid communications, ensure continuity of remote consultations and referral pathways [13–15].

Traditional diesel solutions are insufficient due to fuel logistics vulnerabilities and high operating costs. Smart microgrids, enabled by hybrid inverters and advanced energy management systems, support demand-responsive prioritization of critical clinical loads [6,8]. At the same time, advances in portable and energy-efficient MedTech, such as solar-compatible vaccine refrigerators, point-of-care diagnostic kits, and negative-pressure isolation tents, allow clinics to operate effectively under constrained conditions [10,16–19]. Together, these innovations represent a paradigm shift from reactive relief clinics toward proactive, embedded, and resilient primary care infrastructure [3].

This study aims to design, model, and evaluate FAPCCs for flood-prone regions, with a focus on Southeast Asia. The developed multi-layer systems architecture for FAPCCs integrates energy, clinical, digital, and logistics components. Formulation of a mixed-integer linear programming (MILP) model that couples clinical service reliability with energy dispatch optimization, introducing the continuity-of-care reliability (CCR). Simulation of three archetypal flood contexts—peri-urban delta, inland riverine, and coastal estuary—to evaluate service availability, fuel savings, cold-chain integrity, telemedicine quality, and economic feasibility.

2. Literature Review

The resilience of health facilities has been a concern in disaster risk reduction frameworks. The World Health Organization (WHO) and Pan American Health Organization advocate that hospitals and clinics must remain operational during and after disasters,

emphasizing structural, non-structural, and functional components [1,2]. Studies have highlighted the importance of redundancy in power, water, and supply chains as well as modular building approaches that can adapt to sudden hazards [3,4]. More recent reviews show that embedding climate-resilience measures into primary health infrastructure significantly reduces morbidity and mortality in disaster-prone regions [2,20].

Distributed energy systems, particularly microgrids, have emerged as a core strategy for powering critical facilities during outages. Early frameworks by Lasseter [5] and the United States Department of Energy programs [9] emphasized microgrid islanding, black-start capabilities, and tiered load prioritization. Hybrid configurations of photovoltaic–battery–diesel systems are widely reported to reduce life-cycle cost and improve reliability compared with diesel-only gensets [6–8]. Research shows optimal designs for health facilities typically require 1–3 days of energy autonomy for critical loads, with MILP or model predictive control ensuring service continuity [6,9]. Integration of DERs also contributes to emission reductions and aligns with national decarbonization pathways.

Vaccine and biological sample cold-chains are highly sensitive to power disruptions. The WHO's Performance, Quality and Safety (PQS) system sets stringent requirements for vaccine storage at 2–8 °C [10]. Aranda et al. [11] demonstrated the utility of phase-change materials for maintaining thermal stability, while PATH [12] documented lessons from Cold Chain Equipment Optimization Platforms (CCEOP). Research emphasizes that embedding temperature loggers with real-time monitoring, combined with resilient microgrid power supplies, substantially reduces the risk of vaccine spoilage in flood scenarios [10–12].

Advances in portable MedTech support primary care continuity under disaster constraints. Devices such as battery-powered ultrasound units [18], portable autoclaves [16,17], and negative-pressure isolation tents [19] provide safe clinical operations with low power draw. The WHO and International Organization for Standardization (ISO) standards on sterilization (ISO 11135/17665) ensure quality assurance in decentralized contexts [17]. These modules are increasingly deployed in humanitarian settings, where rapid-deploy capacity is critical [19].

Floods frequently disrupt telecommunications, impeding referral pathways. Hybrid terrestrial-satellite connectivity with software-defined wide area network (SD-WAN) is documented as an effective approach to ensuring reliable bandwidth [13]. Health Level Seven Fast Healthcare Interoperability Resource (HL7 FHIR) standards [14] and the International Telecommunication Union (ITU) emergency telecom guidelines [13] provide interoperability for electronic health records and teleconsults. Empirical field trials of low Earth orbit (LEO) satellite constellations demonstrate median latencies of 250–300 ms, sufficient for telemedicine applications [15]. Collectively, these systems extend the reach of clinicians during flood-induced isolation.

UAVs have been trialed for the transport of blood samples and medical payloads, showing time savings and route redundancy when ground access is blocked [21]. Manyika et al. [22] emphasize their humanitarian applications, though regulatory approval remains a challenge [23]. Complementary USVs allow shallow-draft operations in inundated corridors, expanding the logistical envelope for primary care clinics [21–23].

The safe deployment of flood-adaptive clinics requires compliance with technical standards. International Electrotechnical Commission (IEC) 60364-7-710 and IEC 60601 govern medical electrical installations [24,25], while the Institute of Electrical and Electronics Engineers (IEEE) 1547 defines DER interconnection [8]. Cybersecurity is addressed through IEC 62443 [26], which is increasingly important in microgrid and telemedicine integration. The WHO's Health Emergency and Disaster Risk Management framework [20] further underlines the multi-sectoral coordination needed for resilient primary healthcare.

3. Methodology

Figure 1 illustrates the multi-layer architecture of FAPCC, integrating hazard, structural, energy, clinical, ICT, and logistics layers into a unified system-of-systems model. Flood hazard inputs were characterized using design flood elevation (DFE), inundation duration, grid outage probability, and road inaccessibility probability. Geotechnical parameters (bearing capacity, scour risk) and connectivity maps (cellular coverage, satellite visibility) informed siting decisions. Table 1 summarizes representative hazard profiles for peri-urban, riverine, and coastal archetypes.

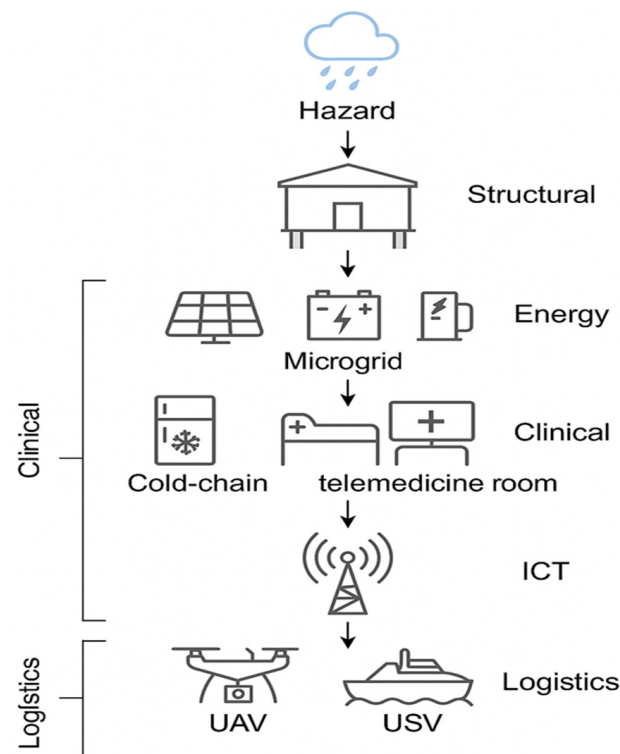


Figure 1. Multi-layer architecture of the FAPCC (hazard, structural, energy, clinical, ICT, logistics layers).

Table 1. Flood hazard profile inputs for peri-urban, riverine, and coastal archetypes.

Parameter	Peri-Urban Delta	Inland Riverine	Coastal Estuary
Design flood elevation (DFE, m)	1.8	3.2	2.5
Inundation duration (days)	5–7	7–10	6–8
Grid outage probability (%)	60	75	70
Road inaccessibility (%)	40	65	55
Ambient temperature (°C)	30 ± 4	28 ± 5	32 ± 3
Humidity (%)	78	82	85
Connectivity coverage	4G/LTE (variable)	3G/4G (weak in pockets)	4G/5G (coastal dense zones)
Satellite visibility	Good	Moderate (tree canopy)	Excellent

Clinical loads were stratified into three tiers: Tier-1 (critical, e.g., vaccine cold-chain, suction, communications), Tier-2 (priority, e.g., ultrasound, centrifuge, HVAC for isolation), and Tier-3 (deferrable, e.g., laundry, EV charging). Table 2 presents daily energy demands by tier for the three archetypes.

Table 2. Daily clinical load taxonomy by tier and archetype.

Load Tier	Service/Device Category	Typical Devices (Examples)	Peri-Urban Delta (kWh/Day)	Inland Riverine (kWh/Day)	Coastal Estuary (kWh/Day)
Tier 1 (critical)	Vaccine cold-chain, essential ICT, emergency lighting	PQS E003 fridge, suction pump, router, radios, LED lighting	12.5	13.2	13.0
	Sterilization (low-cycle)	Portable autoclave, UV-C disinfection	5.0	5.5	5.2
	Essential diagnostics	Particulate organic carbon analyzer, glucometer, battery-powered ultrasound	4.0	4.5	4.2
Tier 2 (priority)	Clinical heating, ventilation, and air conditioning/isolation support	Negative-pressure fans, high efficiency particulate air (HEPA) H14 filtration	6.5	7.0	6.8
	Laboratory support	Centrifuge, incubator, sterilizer	3.5	3.8	3.6
	Extended diagnostics	Portable X-ray, additional ultrasound	4.0	4.5	4.2
Tier 3 (deferrable)	Laundry and sanitation	Washing machine, dryer, water pumps	6.0	6.5	6.3
	Staff support loads	Computers, fans, lighting, and charging stations	3.5	4.0	3.7
	Mobility/ev charging (if applicable)	E-motorbike charging, drone batteries	2.0	2.5	2.3
Total daily demand	—	—	47.0	51.5	49.3

The proposed hybrid system consists of PV arrays (6–20 kWp), LiFePO₄ battery storage (40–120 kWh), and a 12–20 kVA diesel genset with jacket-water heat recovery. Power electronics include a hybrid inverter, DC bus for ICT and refrigeration, and tiered load panels with controllable contactors. Table 3 details DER specifications. Figure 2 provides a one-line diagram of the architecture.

Table 3. DER and balance-of-system specifications.

Subsystem	Component	Specification/Range	Notes
PV	PV array capacity	6–20 kWp (monocrystalline, 500 W modules)	Sized according to load and solar resource
	Mounting	Elevated ground-mount, corrosion resistant	Designed for flood-prone sites
Battery energy storage (BESS)	Storage Capacity (LiFePO ₄)	40–120 kWh	Modular racks, 2nd-life compatible
	Depth of discharge (DoD)	80–90%	Balancing cycle life and usable capacity
	Round-trip efficiency	92–95%	Includes inverter interface losses
Diesel genset	Rating	12–20 kVA	Jacket-water heat recovery for sterilization
	Fuel consumption	0.28–0.32 L/kWh	Optimized for low-load operation

Table 3. Cont.

Subsystem	Component	Specification/Range	Notes
Power electronics	Hybrid inverter	10–20 kVA, grid-forming, black-start capable	Supports PV, BESS, and genset integration
	DC bus	48–120 V DC	Supplies ICT and refrigeration loads
	Load panels	Tiered (critical, priority, deferrable)	Controlled by smart contactors
Balance of system (BOS)	Monitoring and control	energy management system (EMS) with MILP optimization, supervisory control, and data acquisition dashboard	Supports CCR-based prioritization
	Protection	Surge arrestors, molded case circuit breakers, molded case circuit breakers	Complies with IEC 60364-7-710 [17]
	Enclosure	IP65, corrosion-resistant, modular skids	Suitable for tropical flood environments

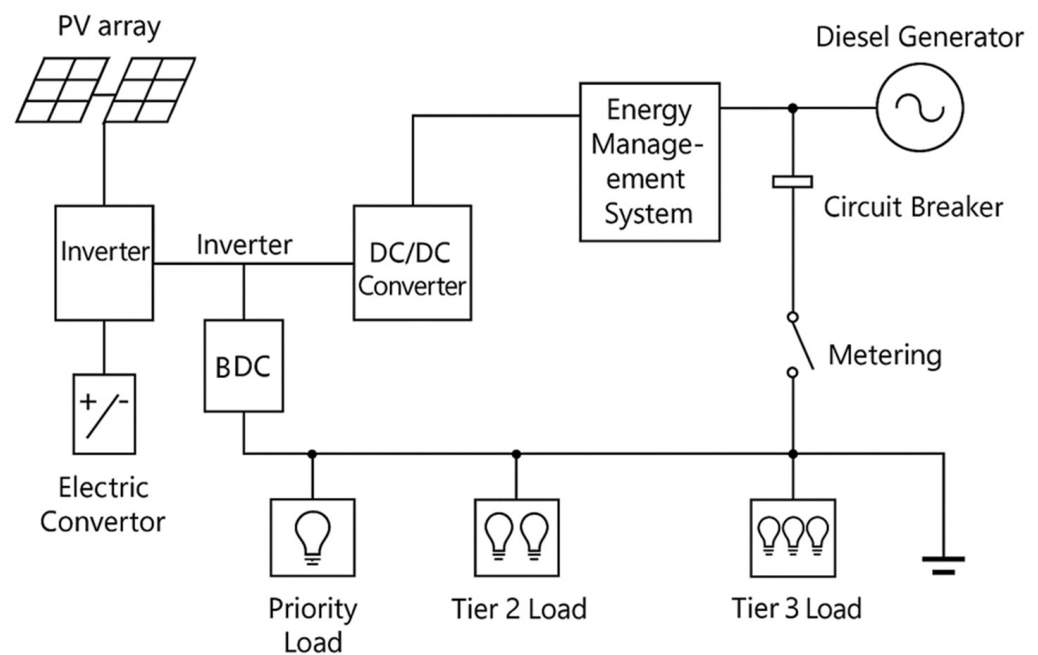


Figure 2. Hybrid PV-BESS-diesel microgrid with tiered load panels.

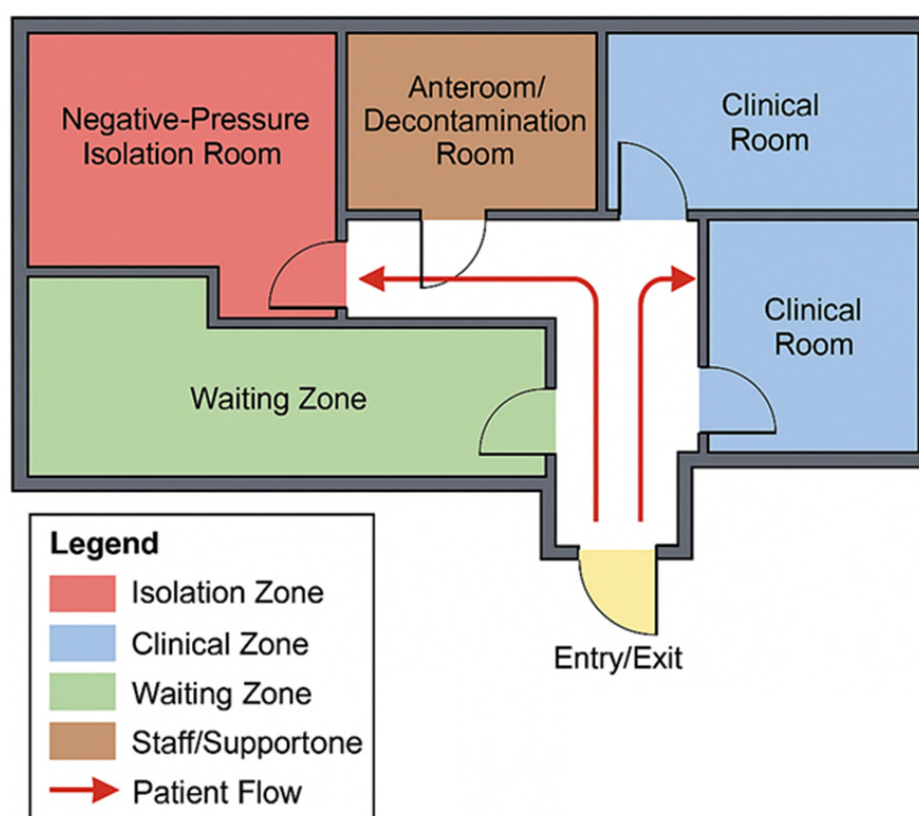
A CCR index is defined to link load availability to clinical service continuity. A MILP-based optimization minimizes net present cost (NPC) while penalizing unmet critical loads and excessive fuel use. Constraints include power balance, state of charge dynamics, inverter/genset ratings, and cold-chain temperature stability.

A lumped resistor–capacitor model simulates vaccine refrigerator temperature dynamics. Door-open events and compressor duty cycles are explicitly modeled. Power allocation prioritizes cold-chain stability within 2–8 °C. Table 4 provides scenario definitions and ambient conditions. The ICT layer comprises SD-WAN routers with dual LTE/5G, LEO satellite backup, and VHF voice fallback. Telemetry uses Modbus/IEC 61850 gateways and resistor–capacitor protocols. Health data are managed via local FHIR-compatible servers with store-and-forward for offline continuity [27].

Table 4. Scenario definitions and ambient conditions.

Parameter	Peri-Urban Delta	Inland Riverine	Coastal Estuary
Scenario duration (days)	7	10	8
Average solar insolation (kWh/m ² /day)	4.8	3.9	5.2
Average ambient temperature (°C)	30 ± 4	28 ± 5	32 ± 3
Relative humidity (%)	78	82	85
Flood depth (m, above DFE)	0.5–1.0	1.0–1.5	0.8–1.2
Inundation duration (days)	5–7	7–10	6–8
Grid outage probability (%)	60	75	70
Road inaccessibility (%)	40	65	55
Connectivity coverage	4G/LTE (variable)	3G/4G (weak pockets)	4G/5G (dense coastal zones)

The infection prevention and control (IPC) layout incorporates zoned patient flows, with negative-pressure isolation rooms (−2.5 Pa), HEPA H14 filtration, and UV-C disinfection adjuncts. Figure 3 illustrates IPC zoning and flows.

**Figure 3.** IPC zoning and patient flow schematic with negative-pressure isolation.

Clinics are elevated to DFE + 0.6 m freeboard with corrosion-resistant materials and sacrificial floodable skirts. Optional pontoon modules enable amphibious deployment. Quick-disconnect umbilicals facilitate rapid evacuation and redeployment. Unmanned systems support specimen transport and pharmaceutical resupply. UAVs carry 2 kg payloads over 20–30 km, while shallow-draft USVs operate along inundated corridors. Figure 4 depicts the logistics chain. Three scenarios (peri-urban delta, inland riverine,

coastal estuary) simulate 7–10 day outages with varying isolation, ambient temperature, and access disruptions. Table 4 outlines these scenarios.

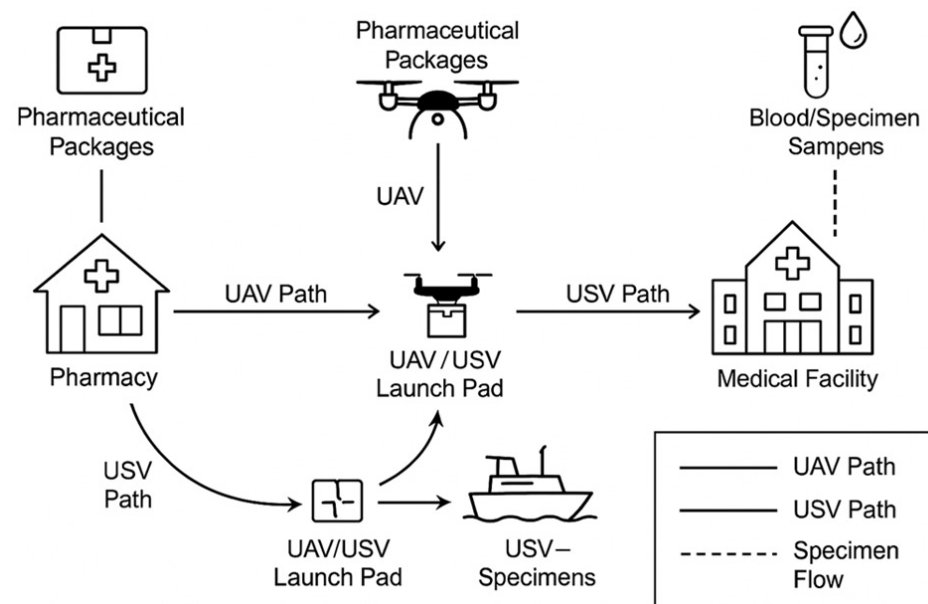


Figure 4. UAV/USV logistics chain for pharmaceutical and specimen transport.

4. Results

Across all three scenarios, optimized systems (PV 12–18 kWp; BESS 60–100 kWh; 15 kVA genset) achieved $CCR \geq 0.995$, ensuring no Tier-1 load shedding. Tier-2 loads, such as laundry and sterilization, were deferred during consecutive low-insolation days. Table 5 highlights the reliability and dispatch summary.

Table 5. Reliability and dispatch summary (CCR, fuel use, PV contribution, BESS cycles).

Metric	Peri-Urban Delta	Inland Riverine	Coastal Estuary
CCR (–)	0.998	0.996	0.997
Fuel use (L)	72	108	89
PV contribution (%)	79	72	75
BESS cycles	9.1	12.3	10.4

Relative to diesel-only baselines, hybrid systems reduced fuel consumption by 62–81%, with proportional CO_2e reductions. Figure 5 compares fuel-use across architectures. Emissions savings directly contribute to ESG performance metrics for health systems.

Vaccine refrigerators maintained 2–8 °C with <0.1% excursion time across all scenarios. Compressor duty increased during high ambient temperatures but remained within system capacity. Table 6 summarizes cold-chain performance.

Table 6. Cold-chain performance metrics (temperature, excursion time, door-open events).

Metric	Peri-Urban Delta	Inland Riverine	Coastal Estuary
Mean chamber temp (°C)	4.1	4.2	4.3
Excursion time (%)	0.05	0.08	0.07
Max door-open events/day	18	21	20

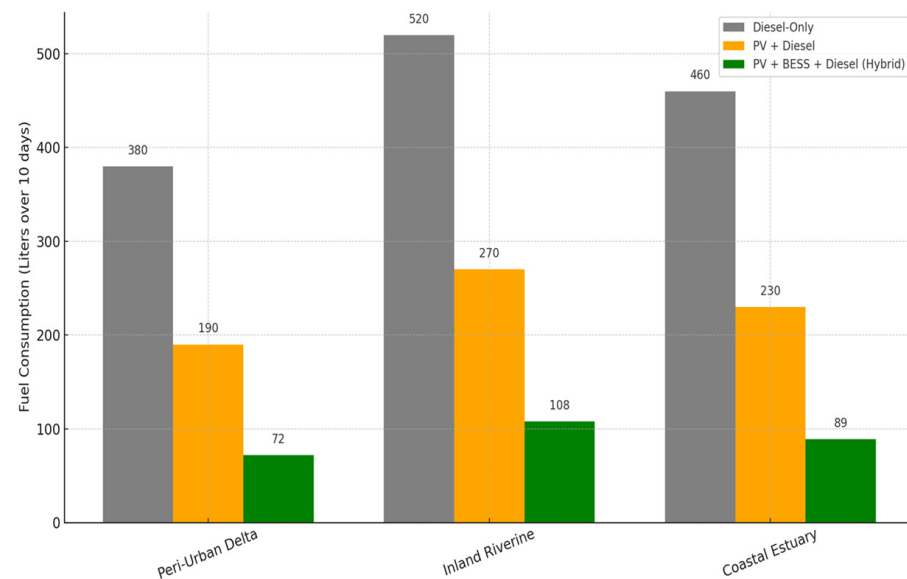


Figure 5. Fuel-use comparison across diesel-only and hybrid systems.

Bonded LTE/5G and satellite links achieved a median uplink latency of 142 ms, with packet loss <0.5%. Under cellular congestion, LEO satellite links sustained <300 ms latency. Table 7 summarizes network performance.

Table 7. Network performance metrics (latency, availability).

Link	Median Latency (ms)	Availability (%)
LTE/5G	128	93
LEO satellite	260	98
Bonded	142	99

Patient throughput decreased by 8–14% compared with baseline due to IPC zoning and triage bottlenecks, not energy shortages. Essential services such as vaccination, maternal care, and urgent triage were maintained. Hybrid microgrids achieved payback in 7.1–9.8 years through fuel savings and avoided service loss. Table 8 presents the economic summary. Table 9 highlights bill-of-materials and circularity features.

Table 8. Economic summary (CAPEX, NPC, payback period).

Scenario	CAPEX (kUSD)	NPC (kUSD)	Payback (Years)
Peri-urban delta	340	465	7.1
Inland riverine	365	512	8.4
Coastal estuary	352	488	7.8

Table 9. Meta-bill of materials with circularity annotations.

Subsystem	Item	Qty	Circularity Features
Energy	PV modules 500 W	36	Recyclable glass/aluminum
Energy	BESS racks 10 kWh	8	Modular, 2nd-life ready
Clinical	Vaccine fridge PQS-E003	1	PCM liners, temp logger
Clinical	Autoclave 23 L	1	Heat-recovery coil
ICT	SD-WAN router	1	Dual SIM, sat failover
Structure	Elevation jack columns	4	Replaceable pads

5. Discussion

The simulation results highlight important tradeoffs in hybrid microgrid sizing. Larger PV arrays improve renewable fraction but require higher upfront capital, while oversized BESSs extend autonomy but risk underutilization. Diesel gensets remain essential for black-start and multi-day overcast periods, though careful right-sizing minimizes wet-stacking and reduces lifecycle operating expenditure. The CCR metric effectively linked energy reliability to service continuity, providing a clinically relevant performance indicator beyond conventional loss of power supply probability.

The clinic maintained uninterrupted Tier-1 services even under extended outages. However, clinical throughput declined by 8–14% due to IPC zoning constraints, triage time, and PPE usage rather than energy shortages. This underscores the importance of balancing energy system resilience with operational design. Negative-pressure isolation, although energy-intensive, proved critical for infection control in flood shelters where communicable disease risk is elevated. Optimized HVAC control and staggered sterilization cycles can reduce peak energy demand without compromising safety.

Maintaining vaccine cold-chain integrity was central to the system design. The thermal modeling validated the resilience of PQS-certified refrigerators under hybrid microgrid operation, with negligible temperature excursions. These findings suggest that prioritization of cold-chain and diagnostic equipment in EMS algorithms is essential for continuity of immunization programs during disasters. Integrating door-open sensors and predictive cooling strategies could further optimize compressor duty cycles.

Hybrid connectivity solutions achieved latency and reliability sufficient for tele-consults and e-referrals. Bonded LTE/5G and satellite links delivered high availability, though the costs of satellite subscriptions may pose barriers. Policy support for subsidized emergency bandwidth could enhance scalability. Store-and-forward EHR functions ensured continuity during temporary outages, aligning with international best practices for disaster telehealth.

UAV and USV integration provided critical redundancy in pharmaceutical and specimen logistics, mitigating the impact of road inaccessibility. Regulatory restrictions on BVLOS flights and medical payload certification remain barriers to operational deployment. Partnerships with civil aviation and maritime authorities are necessary to institutionalize such logistics pathways. Incorporating UAV/USV docking stations in the structural design of clinics enhances flexibility during prolonged inundation.

LCCA demonstrated favorable payback periods (7–10 years) compared with diesel-only systems, largely through fuel savings and avoided service disruption. In addition to direct cost savings, the ESG co-benefits, including reduced carbon emissions, improved health equity, and enhanced resilience, encourage investment. Financing models such as blended finance or climate resilience bonds could accelerate adoption in low-resource settings.

The integration of ICT with energy and clinical systems introduces cyber-physical vulnerabilities. IEC 62443 compliance and segmented networks are vital to prevent malicious interference. Governance frameworks should ensure clear delineation of responsibilities between health authorities, energy operators, and ICT providers. Training for staff on cyber hygiene is as essential as clinical or technical maintenance drills.

FAPCCs provide a scalable model for disaster-resilient primary care. Ministries of Health can embed such clinics into national disaster risk management strategies, while donor agencies can align funding with sustainable development goals (SDG) 3 (health) and 7 (energy). Regional cooperation through ASEAN and other platforms can harmonize standards, logistics corridors, and ICT protocols. Local manufacturing of modular chassis and solar components can reduce costs and improve supply chain security.

6. Conclusions

In this study, FAPCCs are developed by integrating smart microgrids, rapid-deploy medical technologies, and flood-resilient infrastructure to ensure continuity of essential services in flood-prone regions. By linking energy reliability with clinical service continuity using the CCR metric, the research demonstrated that hybrid PV–BESS–diesel microgrids can achieve >99.5% service availability under 7–10 day outage scenarios while significantly reducing fuel dependency and emissions.

In regard to energy resilience, PV–battery–diesel hybrids reduced fuel use by 62–81% compared with diesel-only systems, providing a sustainable pathway to resilient health services. Vaccine cold-chains and diagnostic services were maintained with negligible thermal excursions, safeguarding immunization and primary care continuity. Hybrid LTE/5G-satellite communications sustained telemedicine quality of service with <150 ms latency, supporting remote consultation and referral during isolation. Life-cycle cost analysis showed 7–10 year payback periods, demonstrating that resilience can align with financial sustainability. Modular, amphibious clinic structures with UAV/USV logistics provide flexible deployment in peri-urban, riverine, and coastal archetypes.

The integration of smart microgrids, portable MedTech, and resilient logistics offers a replicable model for Ministries of Health and disaster agencies seeking to safeguard primary care in the context of intensifying climate hazards. Beyond technical feasibility, the findings underscore the importance of embedding FAPCCs into broader disaster risk reduction and health system strengthening frameworks.

Future deployment should prioritize policy alignment with national disaster health strategies and regional frameworks (e.g., ASEAN disaster preparedness). Local manufacturing of modular clinic components and renewable technologies to enhance affordability and supply chain resilience. Capacity building for clinicians and engineers in energy management, infection prevention, and telehealth systems. Pilot programs to validate field performance under real-world hydrological events.

In conclusion, FAPCCs represent a transformative innovation for climate-resilient healthcare, bridging energy, health, and disaster management. Their deployment can help ensure equitable access to primary care, protect vulnerable populations, and advance progress toward Sustainable Development Goals in flood-affected regions worldwide.

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