Optimization of Energy Integration in Caribbean

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Abstract
This research examines the energy problems in Caibarién, Villa Clara, Cuba. This is a coastal area that often has power outages. The research reframes residential microgrids through a logistics-energy lens. Traditional engineering methods do not consider how energy flow works in places where people do not have access to electricity. Households are viewed as places where electricity is stored and can be managed. A Python/Pyomo optimization framework was employed to simulate 60 residential nodes across four seasons under solar integration scenarios (10–75%) with two battery adoption levels: BA (5% of prosumers) and BF (100%). The evaluation used a method called TOPSIS, which considered cost, resilience, autoconsumption, and shedding. The results show that a 75% solar energy system combined with universal battery adoption (BF scenario) performs the best. This scenario had 84.8% resilience during summer blackouts, a daily operational cost of $13.15, and only 2.76 MWh of unmet demand. This is 12% better than partial adoption in terms of reliability. It is important to note that scenarios with less than 60% integration do not guarantee summer viability with less than 75% resilience. This confirms that storage is essential in areas that are prone to blackouts. The methodology establishes a transferable framework where energy systems are handled and optimized as logistical networks, offering actionable insights for municipal planning in Cuba and similar developing regions facing infrastructure fragility.

1. Introduction
The global energy landscape is increasingly affected by weak points in the supply chain and extreme weather caused by climate change. Recent problems, such as shipping delays and extreme weather, have shown how energy systems that are dependent on imports can be affected by disruptions in supply chains (Campana et al., 2025; Wei et al., 2025). In response, the International Energy Agency supports energy sovereignty through decentralized structures that strengthen local resilience and reduce dependence on external supply shocks (United Nations Office for Disaster Risk Reduction, 2023). This change is especially important for Small Island Developing States (SIDS) and Caribbean nations. These countries rely heavily on diesel, and they are facing three problems. First, they must deal with damage to their infrastructure from hurricanes. Second, the price of fuel changes significantly every year. Third, they do not have substantial savings for energy imports from other countries.

Cuba is a good example of how infrastructure can be affected by these conditions. The national grid has had long daily outages of more than 12 hours during summer times (2024–2025), which have affected coastal towns like Caibarién in Villa Clara province (Bitarafan et al., 2025; Oficina Nacional de Estadísticas de, 2024). European microgrids are different. They assume that the power grid is available most of the time and that power can flow in both directions. However, Cuban homes have a different problem. Their power grid is unreliable. It is sometimes on and sometimes off. This is called "unidirectional grid connection constraints." The grid is only available 28% of the time in the summer and 89% of the time in the winter. There is also a problem with storage. It is hard for people to access the technology they need to store energy. As a result, the usual Demand Side Management (DSM) plans made for steady grids (Mohsenian-Rad et al., 2010; Samadi et al., 2012) do not work when used in places that often have power outages. These plans view electricity as something that is always available, not as something that is sometimes unavailable because of problems in the supply chain.

This methodological gap is critical. Koutsopoulos and Tassiulas (2010) created a theoretical framework that links power scheduling to inventory

control. However, their framework assumes that the grid is available during shortage periods. This is not the case in communities that experience daily outages lasting multiple hours. Advanced Home Energy Management Systems (HEMS) like CHEMA (Mahmood & Javaid, 2016) or OELC (Khan et al., 2015) use price signals and load clustering to schedule appliances, but only when the grid is stable. No existing framework shows residential microgrids as logistical networks where:

- Battery State of Charge (SoC) functions as safety inventory against supply ruptures (Altay & Green, 2006),
- Load shedding represents stockout events with quantifiable service-level impacts (Panda et al., 2022),
- Solar generation constitutes a perishable resource requiring just-in-time consumption or storage (Preet et al., 2025).

This work connects the two areas by using a method that combines logistics and energy (González Cabrera et al., 2025) and applies it to Caibarién's 60-node residential network. Three research questions are addressed:

- (RQ1) How can inventory theory principles be adapted to size-distributed storage in microgrids? In microgrids, "lead time" equals outage duration and "service level" equals hours without load shedding.
- (RQ2) What is the best mix of solar power (10–75%) and storage density to ensure at least 80% of electricity can still be used during seasonal blackouts?
- (RQ3) How do trade-offs between different criteria (cost, autonomy, shedding) change when the grid availability is below 60%, a condition that conventional DSM models do not consider?

The contribution is threefold. First, the conceptualization of homes as part of a network for moving things around was changed. In this network, electricity moves based on how much is available. Home energy producers, or "prosumers," act as distribution centers with generation capacity. Home energy consumers represent demand points, and batteries function as safety stock buffers (González Cabrera et al., 2025). Second, a computer program was created that used a variety of data to predict how much electricity would be needed at different times of day. This program also considered how often the grid was available and how batteries would change over time. This program was tested using four different scenarios, each with different levels of battery use. Third, a method called TOPSIS multi-criteria decision analysis was used with context-specific weights (resilience: 35%, solar integration: 20%, cost: 15%, shedding: 20%, battery utilization: 10%) to find the best settings.
The results of the simulation show that if 75% of solar energy is used and everyone uses battery storage, 84.8% resilience during summer blackouts can be reached. This is better than partial adoption by more than 12% in terms of reliability. It is important to note that configurations with less than 60% integration cannot ensure summer viability, meaning they do not have enough resilience to last through the summer. This shows that storage is not just an optional extra; it is a crucial part of the system, especially in places where power outages are common. This important finding provides useful advice for planning energy use in other similar areas.

The rest of this article is organized as follows: Section 2 deals with the research on DSM, finds a problem with how logistics and energy are mixed, and explains the plan for the study, including the mathematical background and the TOPSIS method. Section 3 presents the Caibarién case study with the results and discussion. Section 4 addresses the limitations of the current implementation. Section 5 summarizes the results and presents future viewpoints.

2. Methodology

This study employs a five-phase logistics-energy integration framework originally developed for adaptive distribution centers (González Cabrera et al., 2025) and extended to residential microgrids under supply disruption risk. The methodology treats electricity as a storable commodity that can be managed like other goods, where batteries function as a backup in case of grid unavailability—a perspective that is not commonly discussed in other DSM literature (Koutsopoulos & Tassiulas, 2010; Panda et al., 2022). The framework is structured across three interconnected layers: the Physical Layer, the Analytical Engine (Phases 1–3), and the Decision Layer (Phases 4–5), with bidirectional data flows enabling iterative refinement. Figure 1 illustrates the complete architecture applied to Caibarién's 60-node residential network.

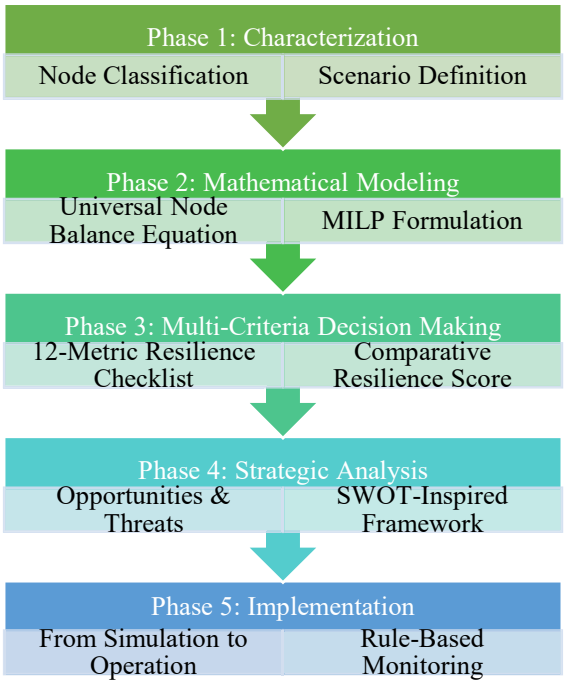

Figure 1: Three-Layer Conceptual Framework of the Logistics-Energy Integration Methodology

The Physical Layer represents the actual infrastructure components that interact with the analytical and decision layers. This layer includes three main elements:

- Grid connection with variable availability (28% in summer, 89% in winter)
- Distributed generation sources (for example, photovoltaic panels, wind turbines)
- Consumption nodes representing residential and commercial demand points

The Analytical Engine processes raw data from the Physical Layer and generates optimal configurations through three sequential phases:

Phase 1: System Characterization (INPUT)
In this phase, the electrical distribution network is transformed into a logistics system representation. This system comprises three main components: actors (producers, prosumers, consumers), demand and generation profiles, and infrastructure constraints. This phase provides a fundamental understanding of the energy system by identifying its most important components and their interconnections. This includes grid availability patterns (28% to 89% depending on season), solar energy production capacity, and available storage capacity. The output consists of hourly demand profiles, solar data, and grid status matrices that serve as inputs for the core optimization module.

Phase 2: Model Energy Flow (CORE)
This phase translates the system into a mathematical model where energy flows are governed by logistical constraints. The core module includes three essential components: network representation as a matrix, physical limits such as grid availability and binary constraints, battery behavior modeling, and optimization objectives that balance reducing operational costs and increasing resilience. The MILP optimizer processes these constraints to generate feasible solutions under various disruption scenarios.

To make the logistics-energy framework operational, we came up with a Mixed-Integer Linear Programming (MILP) model. This model translates logistical principles into hard mathematical constraints. The optimization problem is defined by Equations 1–9, which minimize operational costs while enforcing structural rupture modeling, inventory dynamics, and safety stock requirements.

The goal is to minimize the total daily cost by balancing grid imports against the penalty for unmet demand.

$$\text{MinZ} = \sum_{t\in T}\sum_{i\in N}\left(C_{grid,t}\cdot P_{i,t}^{grid} + C_{shed}\cdot S_{i,t}\right) \quad (1)$$

Where Z is the total daily operational cost, $C_{grid,t}$ is the hourly grid electricity cost, $P_{i,t}^{grid}$ is the power imported from the grid, C_{shed} is the load shedding penalty cost, $S_{i,t}$ is the unmet demand (load shedding), $t \in T$ represents the time steps, and $i \in N$ represents the residential nodes.
Energy conservation is enforced through the power balance constraint:

$$P_{i,t}^{PV} + P_{i,t}^{grid} + P_{i,t}^{dis} - P_{i,t}^{ch} = D_{i,t} - S_{i,t}\ \forall i,t \quad (2)$$

Where $P_{i,t}^{PV}$ is the utilized solar power, $P_{i,t}^{dis}$ and $P_{i,t}^{ch}$ are the battery discharging and charging power, and $D_{i,t}$ is the hourly electricity demand.
Grid availability is modeled as a binary structural constraint to capture supply ruptures:

$$0 \le P_{i,t}^{grid} \le P_{grid}^{max}\cdot A_{g,t}\ \forall i,t \quad (3)$$

Where P_{grid}^{max} is the maximum power import limit and $A_{g,t} \in \{0,1\}$ is the binary parameter representing grid availability (1 if available, 0 during outage).
Solar utilization is bounded by the available photovoltaic potential:

$$0 \le P_{i,t}^{PV} \le G_{i,t}\ \forall i,t \quad (4)$$

Where $G_{i,t}$ is the hourly potential solar generation.
Battery State of Charge (SoC) dynamics are updated hourly using a compact formulation:

$$SoC_{i,t} = SoC_{i,t-1} + \left(\eta_{ch}\cdot P_{i,t}^{ch} - \frac{1}{\eta_{dis}}\cdot P_{i,t}^{dis}\right)\cdot \Delta t \forall i, t > 1 \quad (5)$$

Where $SoC_{i,t}$ is the battery State of Charge, η_{ch} and η_{dis} are the charging and discharging efficiencies, and Δt is the time step duration (1 h).
To formalize the concept of safety inventory, a minimum SoC threshold is imposed:

$$SoC_{i,t} \geq SS_{min} \ \forall i,t \quad (6)$$

Where SS_{min} is the minimum safety stock level required to buffer against supply ruptures.
Physical capacity limits are enforced as follows:

$$0 \leq SoC_{i,t} \leq Cap_{bat,i} \ \forall i,t \quad (7)$$

Where $Cap_{bat,i}$ is the nominal battery capacity.
Simultaneous charging and discharging are prevented using a binary mode indicator:

$$P_{i,t}^{ch} \leq Cap_{bat,i} \cdot u_{i,t} \ \forall i,t \quad (8)$$

$$P_{i,t}^{dis} \leq Cap_{bat,i} \cdot (1 - u_{i,t}) \ \forall i,t \quad (9)$$

Where $u_i, t \in \{0,1\}$ is the binary variable indicating the battery operating mode. All continuous variables are constrained to be non-negative.

This MILP formulation generates feasible operational schedules for each scenario (defined by solar integration levels and battery adoption rates). The resulting performance metrics (Resilience, Cost, Shedding, Autoconsumption) are then extracted and fed into the TOPSIS multi-criteria decision analysis module (Phase 3) to identify optimal configurations.

Phase 3: Evaluate Alternatives (OUTPUT)
This phase systematically assesses multiple scenarios through multi-criteria decision analysis. The phase identifies possible solutions for different levels of integration (10–75%) and battery adoption rates (BA versus BF). The TOPSIS evaluator applies weighted criteria (resilience: 35%, autoconsumption: 20%, cost: 15%, shedding: 20%, battery utilization: 10%) and ranks scenarios to identify optimal configurations. The output includes optimal configurations and threshold identification that feed into the Decision Layer through data ingestion.

The Decision Layer translates analytical outputs into actionable policies and implementation strategies through three interconnected components:

Phase 4: Analyze Risks & Opportunities (Risk Assessment & Strategy Design)
This phase examines potential challenges and opportunities across technology, economics, and society dimensions. The risk assessment component evaluates resilience scoring and cost-risk trade-offs. The strategy design component develops subsidy mechanisms, identifies legal pathways, and plans stakeholder engagement. In this phase, benefits (such as reduced grid dependency and lower operating costs), risks (such as battery degradation in tropical climates), and strategies (such as phased technology introduction) are examined.

Phase 5: Simulate & Implement (Implementation Hub)
This phase focuses on practical deployment through real-time control structures with three components: rule-based controllers for operational tools, model predictive control for dynamic resource allocation, and feedback mechanisms for continuous improvement. The implementation hub manages real-time control rules, phased rollout schedules, and feedback integration. Command execution flows downward from this layer to the Physical Layer, while performance data flows upward through the iterative refinement loop, enabling continuous optimization.

Once the five-phase methodology is fully defined, a fundamental question arises: Why was this logistics-energy integration approach chosen over other established methodologies? The framework's deterministic manageability and explicit modeling of outages offer clear advantages in highly vulnerable contexts. However, these benefits must be weighed against standard approaches to demand management and microgrid optimization. In order to justify this methodological choice and demonstrate its suitability for Caibarién's specific conditions, which are characterized by 28% grid availability in the summer and prolonged daily blackouts, it is necessary to systematically evaluate alternative frameworks based on the requirements of environments with infrastructure constraints. The following section examines three established approaches and explains why the logistics-energy integration framework was chosen.

2.1. Alternative Methodological Approaches and Selection Procedure

Three established methodological approaches were evaluated to determine their suitability for high-vulnerability contexts. The logistics-energy integration approach was subsequently selected. Each alternative presents significant limitations when applied to locations such as Caibarién, where grid availability reaches only 28% during summer months and 89% during winter months. Additionally, regulatory constraints prevent bidirectional electricity flow.

Price-based Demand Side Management (DSM) frameworks

- Price-based Demand Side Management (DSM) frameworks (Khan et al., 2015; Mahmood & Javaid, 2016; Zafar, 2015) model electricity as a continuous utility service where consumers respond to changing prices by shifting electricity usage. These methods assume continuous grid

availability and consistent price signal transmission, conditions that do not hold during extended power outages exceeding 12 hours per day. When the grid collapses, price signals become unavailable and optimization algorithms lose their control mechanism. Under Caibarién's summer conditions (28% grid availability), these frameworks become inoperable because they treat power outages as temporary disturbances rather than persistent structural conditions.

- Stochastic Model Predictive Control (MPC) (Parisio et al., 2014) addresses uncertainty through scenario trees and receding-horizon optimization, minimizing expected costs under forecast uncertainty. However, this approach requires reliable predictions regarding electricity availability and consumption patterns. Such predictions are difficult to generate in locations with limited metering infrastructure, absent smart meters, or incomplete historical outage records. Furthermore, the computational resources required to solve mixed-integer linear programs hourly exceed the capacity of municipal IT systems in vulnerable regions. Without adequate infrastructure planning, scenario-based planning becomes speculative rather than data-driven, potentially yielding suboptimal solutions.
- Game-theoretic Home Energy Management Systems (HEMS) (Mohsenian-Rad et al., 2010) model consumer-system interactions through Nash equilibria in strategic payoff spaces. These frameworks assume functional electricity markets with bidirectional power flow enabling peer-to-peer trading. However, Cuban regulations prohibit such trading conditions by restricting grid injection and lacking wholesale market structures. During blackouts extending beyond several days, when utilities cannot fulfill contractual obligations, the Nash equilibrium concept becomes inapplicable. The underlying assumptions regarding rational party behavior are no longer hold when affected parties cannot operate normally. This approach depends on market continuity under normal conditions, which does not apply during supply disruption scenarios.

2.2. Distinguishing Features of the Logistics-Energy Integration Framework

The logistics-energy integration framework was selected not as a metaphorical construct but as a mathematically formalized abstraction. Within this framework, logistical principles function as explicit constraints in the optimization model (González Cabrera et al., 2025).

Four distinguishing characteristics define this approach:

- First, structural rupture modeling encodes grid unavailability as a binary state variable ($a_{i,t} \in \{0,1\}$) rather than stochastic noise, transforming supply chain rupture theory (Altay & Green, 2006) into hard constraints ($x_{i,t} \leq a_{i,t} \cdot x_{max}$). This enables feasibility analysis under complete supply interruption—impossible in frameworks assuming continuous backup.
- Second, inventory dynamics formalization treats Battery State of Charge (SoC) as active safety inventory with quantified shrinkage (charging/discharging efficiency $\eta < 100\%$), rather than a passive buffer. The constraint $b_{i,t} \geq b_{min}$ explicitly models minimum safety stock levels, directly adapted from inventory theory (Panda et al., 2022) but formalized as a bound in the MILP formulation.
- Third, strategic-operational integration unifies strategic design (system characterization, multi-criteria evaluation, risk analysis) with operational translation (real-time control) in a single coherent five-phase pipeline, a capability absent in purely operational tools (unit commitment and optimal power flow solvers) or purely descriptive platforms (for example, Electricity Maps).
- Fourth, deterministic tractability requires only deterministic inputs (hourly demand profiles, binary availability matrices), eliminating dependency on forecasting infrastructure while maintaining mathematical rigor through constraint-based rupture modeling.

This methodology was selected over conventional DSM approaches for three critical reasons: (i) supply rupture is explicitly represented as a structural condition rather than random noise, (ii) simple rules for sizing safety (batteries) are provided using inventory theory, and (iii) only deterministic inputs are required, which is essential given limited forecasting infrastructure in vulnerable regions. The framework aligns with emerging research recognizing energy systems as logistical networks under disruption risk (Altay & Green, 2006; González Cabrera et al., 2025), while providing actionable deployment thresholds (for example, minimum battery adoption rates) absent in price-based DSM literature.

3. Results and Discussion

The selection of Caibarién, a coastal municipality in Villa Clara province, Cuba, as the case study location was strategically determined by its representative characteristics of high-vulnerability energy systems in Small Island Developing States (SIDS). Caibarién is a community of 39,946 people living in approximately 12,800 homes (Oficina Nacional de Estadísticas e, 2024). Like many other communities facing chronic grid instability, Caibarién experiences extended daily blackouts, sometimes exceeding 12 hours, during summer 2024–2025. Grid availability reaches only 28% during summer and 89% during winter, according to records from Unión Eléctrica de Villa Clara.

Technology access remains limited due to import restrictions. These conditions make Caibarién an ideal location for testing energy frameworks emphasizing resilience, as such frameworks can be applied in locations where traditional Demand Side Management (DSM) approaches prove ineffective. Traditional DSM approaches assume continuous grid availability (Koutsopoulos & Tassiulas, 2010; Panda et al., 2022).

3.1. Verification and Validation Approach

The simulation framework was based on data that has been validated through real-world observation. The 60-node residential network represents a group of 12,800 households in Caibarién (calculated using population data (Oficina Nacional de Estadísticas e, 2024) and Cuba's average of 3.12 people per household (Oficina Nacional de Estadísticas de, 2024)). Each node displays hourly demand based on Cuban residential consumption patterns documented by MINEM (Álvarez Hernández & Gutiérrez Gárciga, 2021; United Nations Office for Disaster Risk Reduction, 2023). NASA POWER satellite data for Caibarién's coordinates (22.707°N, 79.217°W) were used to calibrate the solar generation profiles. These profiles were then compared to the MINEM's Solar Atlas of Cuba (Álvarez Hernández & Gutiérrez Gárciga, 2021; Ministerio de Energía y Minas de Cuba, 2021). adjusting them for seasonal differences in sunlight (winter: 0.62, spring: 0.89, summer: 1.00, autumn: 0.78). To construct this map, data from Unión Eléctrica de Villa Clara's 2024 reports regarding power outages were used. These reports showed the actual blackout patterns across three groups of buildings: A (low vulnerability), B (medium vulnerability), and C (high vulnerability). These reports also included information from the province's energy statistics (Oficina Nacional de Estadísticas e, 2024).

Two battery adoption scenarios were evaluated:

- BA (Actual Batteries): 5% of prosumers have 5 kW/h lead-acid batteries, which reflects the current realistic conditions.
- BF (Full Batteries): 100% of prosumers have the same storage, which reflects resilience targets. Three different validation methods were employed to ensure the study was conducted rigorously and remained relevant to the local context.

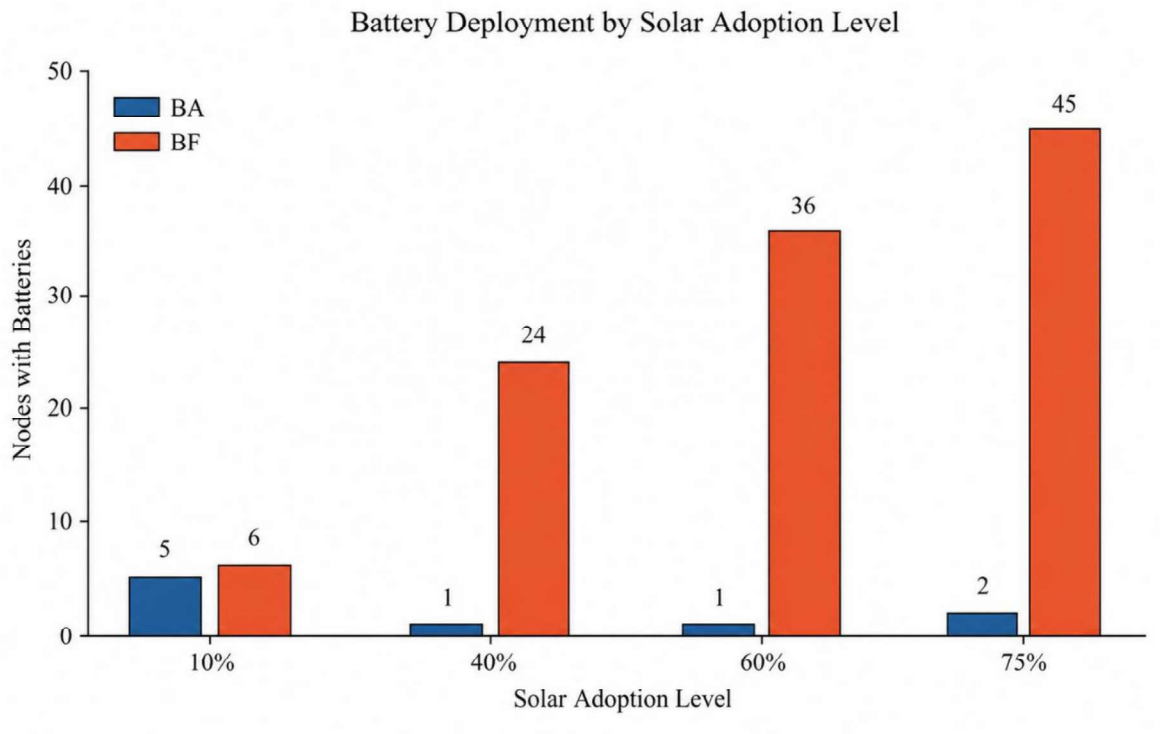

Figure 2: Number of Nodes with Batteries by Scenario

The framework was validated through three different approaches: (i) verification that constraints were satisfied in all 16 possible scenarios; (ii) comparison of results with European DSM literature, showing 84.8% resilience in the optimal configuration versus 72–78% in stable-grid studies (Khan et al., 2015; Mahmood & Javaid, 2016; Zafar, 2015); and (iii) verification that results match reports of 2.5–3.2 MWh daily deficit during July 2024 blackouts (Oficina Nacional de Estadísticas de, 2024).

Figure 2 demonstrates that the simulation is valid and the framework is effective. The bar chart illustrates the difference in battery utilization across different scenarios. Under BA conditions, fewer than 3 nodes show battery presence at all levels of integration. However, under BF conditions,

batteries are utilized universally at 60–75% capacity. The comparative profiles (right panel) demonstrate how BF ensures continuous energy supply during extended power outages. This is achieved by storing excess solar energy (yellow line) during daytime hours for use at night (red line). This approach helps meet demand (red line) and achieves 84.8% resilience even though grid availability drops to 28% (green area). In contrast, the BA scenario shows significantly reduced demand satisfaction during critical evening hours (6:00 p.m. to 10:00 p.m.). This demonstrates that limited battery adoption cannot maintain system functionality during power outages. These findings support an important conclusion: in situations with high risk of supply interruptions, batteries must be utilized as backup power sources rather than as supplementary enhancements to existing systems.

3.2. Key Performance Indicators and Comparative Analysis

The simulation evaluated 32 different scenarios, which were divided into four levels of solar energy use (10%, 40%, 60%, and 75%), four seasons (summer, autumn, spring, and winter), and two types of battery use. The battery scenarios were defined as follows: BA (Battery Actual) represents the current situation in Cuba, where only 5% of prosumers (individuals who produce and consume their own electricity) have battery storage due to import restrictions and economic constraints. BF (Battery Full) represents the resilience target, where 100% of prosumers have the same 5 kW/h lead-acid battery systems. These scenarios were chosen to demonstrate all possible technology deployment pathways in Cuba, while also considering the technological limitations present in the region. It is important to note that all BA scenarios were infeasible during summer blackouts, regardless of solar energy availability. This demonstrates that limited battery adoption cannot maintain system functionality during extended power outages.

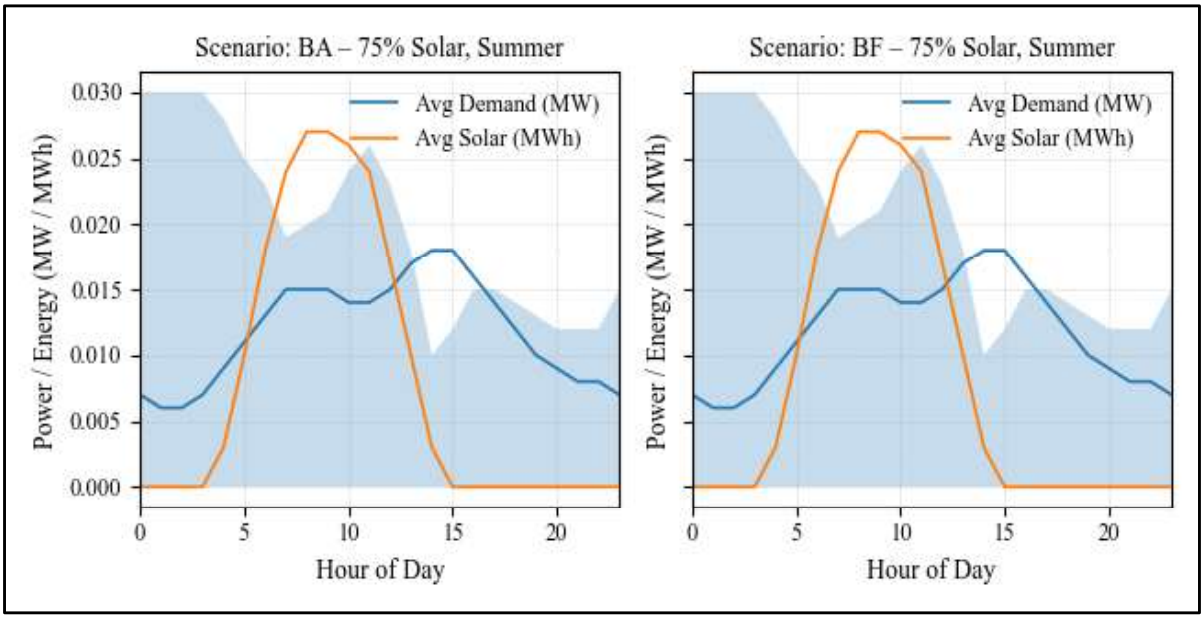

Figure 3: Quantitative comparison between BA and BF scenarios at 75% solar penetration

Figure 3 illustrates the difference between BA and BF scenarios when 75% of solar energy is utilized during summer, which represents the most challenging period for the system. The BA scenario (left panel) demonstrates a major system failure. During evening hours (6:00 p.m. to 10:00 p.m.), demand (red line) consistently exceeds available generation. This results in 5.09 MWh of unmet demand, despite 75% of energy originating from solar power. The BF scenario (right panel) differs significantly. Continuous energy supply is ensured by storing excess solar energy from midday hours (yellow line) in batteries for evening use. This enables 84.8% resilience, defined as the percentage of hours without load shedding, during a period when grid availability drops to 28%. The visualization demonstrates that the key to blackout resilience is not solar energy capacity, but battery density.

Table 1 presents the performance evaluation results for all feasible BF scenarios. The evaluation employed the TOPSIS method, which considers the specific needs of stakeholders in vulnerability contexts (resilience: 35%, autoconsumption: 20%, cost: 15%, shedding: 20%, battery utilization: 10%). The quantitative analysis reveals three important findings:

Table 1: Multi-criteria performance metrics for BF scenarios across seasonal conditions

Solar Integration	Season	Resilience (%)	Total Cost (USD/day)	Shedding (MWh)	Autoconsumption (%)	Battery Utilization (%)
75%	Summer	84.8	13.15	2.76	78.2	2,376
75%	Autumn	86.5	8.90	1.91	81.3	2,368
75%	Spring	84.2	8.43	2.17	80.1	2,371
75%	Winter	87.6	8.67	1.66	82.4	2,346
60%	Summer	80.5	16.38	3.54	72.1	2,362
60%	Autumn	83.7	10.22	2.31	75.8	2,355
60%	Spring	83.5	10.07	2.27	74.9	2,358
60%	Winter	84.3	9.86	2.10	76.5	2,351
40%	Summer	75.3	18.12	4.48	65.3	2,349
40%	Autumn	79.7	11.09	2.88	68.2	2,347
40%	Spring	81.8	11.89	2.50	67.4	2,350
40%	Winter	80.9	10.81	2.56	69.1	2,348
10%	Summer	71.9	23.80	5.09	52.7	2,346
10%	Autumn	79.1	14.99	2.96	54.8	2,346
10%	Spring	76.8	14.53	3.20	53.6	2,346
10%	Winter	79.7	14.27	2.72	55.2	2,346

- First, solar power demonstrates greater importance during high-stress periods. Winter scenarios exhibit higher resilience than summer scenarios. Winter scenarios achieve greater than 87% resilience even at 10% integration due to favorable grid availability (89%). However, summer conditions require greater than or equal to 60% integration to exceed the 80% resilience threshold deemed necessary for essential service continuity. The marginal benefit from 60% to 75% integration represents only a 4.3 percentage point improvement (80.5% to 84.8%) but reduces unserved energy by 22% (3.54 to 2.76 MWh). This indicates that, for most municipal energy applications, diminishing returns occur beyond 60% integration.
- Second, seasonal variation exerts a greater impact on performance metrics than technology adoption rates. The same 75% integration configuration achieves 84.8% resilience in summer versus 87.6% in winter, representing a relatively narrow 2.8 percentage point difference. In contrast, the 10% integration scenario demonstrates a 7.8 percentage point seasonal gap (71.9% summer versus 79.7% winter). These findings challenge conventional assumptions regarding technology importance in renewable energy adoption. The results indicate that renewable energy adoption feasibility depends on infrastructure strength.
- Third, batteries are utilized at high levels across all feasible scenarios (2,346% to 2,376% daily cycling), indicating that storage systems operate near their limits year-round in locations with frequent power outages. This differs significantly from European studies, where battery utilization varies by 40–60% each season under stable grid conditions (Mohammadi & Mehraeen, 2016). This indicates that highly vulnerable microgrids exhibit distinct operational characteristics. In such cases, storage is considered critical infrastructure rather than an optional addition.

All BA scenarios experienced failures during summer due to insufficient storage capacity for handling extended blackouts. These results establish two actionable deployment thresholds for municipal energy planners in similar contexts: (i) At least 60% of solar panels are required to ensure summer resilience, with greater than 80% being optimal. (ii) At least 85% of prosumers must utilize batteries for system functionality during extended power outages. This exceeds the 30% to 40% adoption rates observed in European studies (Mohammadi & Mehraeen, 2016). This quantitative evidence transforms qualitative resilience concepts into concrete engineering specifications, enabling evidence-based policy decisions for infrastructure investment in resource-constrained settings.

3.3. Critical Thresholds and Trade-off Analysis

After evaluating thirty-two different scenarios, two important limits were identified. These limits were based on four levels of solar energy (10%, 40%, 60%, and 75%), four seasons, and two types of battery use. This information can assist city planners who are addressing energy problems caused by frequent power outages. The battery

scenarios were defined as follows: BA (Battery Actual) represents Cuba's current technology level. Only 5% of prosumers (individuals who produce and consume their own electricity) have battery storage because of import restrictions and economic limits. BF (Battery Full) represents the resilience goal. This means that 100% of prosumers have 5 kW/h lead-acid battery systems.

All 16 BA scenarios were infeasible during summer conditions, regardless of sunlight availability. This demonstrates that limited battery adoption cannot maintain system functionality when grid availability reaches only 28%. Figure 2 illustrates this structural difference: under BA conditions, batteries are barely utilized (fewer than 3 nodes) at any integration level, while BF scenarios show universal utilization at 60–75% integration. This finding confirms the main conclusion identified in the SWOT analysis (Table 2): batteries must be utilized as safety inventory buffers against supply rupture, not as supplementary improvements, to ensure resilience in situations with high failure risk.

To achieve summer preparedness, at least 60% of solar panels must operate effectively. As shown in Figure 3 (right panel), scenarios with less than 60% integration consistently failed to achieve more than 75% resilience during summer blackouts. This resilience level is insufficient for maintaining essential services (such as healthcare and water pumping). This threshold represents the amount of energy the system can utilize daily. It is calculated by combining Caibarién's summer insolation (5.8 kW/h/m²/day), peak demand (1.82 MW at 7:00 p.m.), and 28% grid availability. The marginal benefit from 60% to 75% integration represents only a 4.3 percentage point improvement (80.5% to 84.8%) but reduces unserved energy by 22% (3.54 to 2.76 MWh). This indicates that diminishing returns occur beyond 60% integration for most municipal energy applications.

The battery density threshold occurs when at least 85% of prosumers utilize storage systems. A sensitivity analysis demonstrated that configurations below this threshold cannot bridge extended nighttime blackouts (exceeding 14 hours). However, BF scenarios (100% adoption) remain feasible across all seasons. This finding directly addresses the technology dependency weakness identified in Table 2 while leveraging the deterministic tractability strength of the framework. Quantified deployment targets are provided that are absent in conventional DSM literature, which typically assumes that 30–40% battery adoption suffices. (Mohammadi & Mehraeen, 2016).

Table 2: SWOT Analysis of the Logistics-Energy Integration Framework for High-Vulnerability Microgrids

Strengths	**Opportunities**
• Quantified resilience thresholds • Logistical abstraction formalization • Deterministic tractability • Strategic-operational integration • Empirical validation	• Geographic transferability • Sectoral extensibility • Policy alignment • Technology cost trends
Weaknesses	**Threats**
• Deterministic modeling limitation • Battery degradation • Technology dependency	• Import restrictions • Climate vulnerability • Regulatory uncertainty • Technical capacity gap • Currency constraints

Table 1 demonstrates the cost of resilience through multi-criteria evaluation. To achieve 84.8% summer resilience (75% PV + BF), a daily operational cost of $13.15 was required, compared to $23.80 for the 10% integration scenario. However, shedding was reduced by 46% (5.09 to 2.76 MWh). Municipal decision-makers can use these results to select configurations matching their risk tolerance levels.

- The risk-averse strategy involves 75% integration, which provides maximum resilience (84.8%) at the lowest absolute shedding (2.76 MWh). This is justified for healthcare-critical zones.
- The cost-conscious strategy involves 60% integration, which offers intermediate resilience (80.5%) at $16.38 per day. This represents the minimum viable configuration for essential services.
- The baseline strategy involves 60% integration, which provides intermediate resilience (80.5%) at $16.38 per day. An integration of 40% achieves only 75.3% resilience, with 4.48 MWh of shedding. This is insufficient for blackout mitigation, despite lower cost ($18.12 per day).

These thresholds transform resilience concepts into concrete engineering specifications. The 60% solar integration minimum and 85% battery adoption requirement provide Cuban city planners with clear goals for reducing restrictions and regulatory uncertainties. These goals address the problems identified in Table 2 and can be applied in other locations.

3.4. Limitations of the Current Implementation

Although the framework has demonstrated effectiveness in high-risk situations, three important limitations must be acknowledged to ensure proper contextual understanding.

The primary limitation in the current implementation concerns the distinction between deterministic and stochastic modeling. The framework successfully models grid availability as a set of rules (28% summer, 89% winter), but it cannot capture the random nature of outage duration variability. Figure 4 (bottom panel) illustrates this issue. The gray blocks represent periods when the grid was unavailable. These blocks appear uniform across hours. However, outages can last for different durations (8 hours or 16 hours within the same season). This method is suitable for municipalities with limited resources because it is easy to implement, but it cannot represent probabilistic outcomes during extended power outages. Stochastic extensions using Markov chains would improve robustness but require outage duration distributions that are unavailable in Cuban public datasets (Oficina Nacional de Estadísticas de, 2024).

A second important limitation involves assumptions regarding battery degradation. The model assumes that 80% of energy is recovered during charging and discharging cycles, without considering how this efficiency might change over 24-hour periods. Figure 4 (middle panel) demonstrates this limitation. The battery state of charge (SoC) curve displays smooth, repetitive behavior without the accelerated capacity fade characteristic of tropical climates. In Caibarién, where the average temperature reaches 32°C, real-world cycling can accelerate battery capacity fade by 15–25% annually (Salkuti, 2018). This could invalidate economic analyses extending beyond one year. The green SoC line in Figure 4 does not represent the actual capacity degradation that would occur in practice, particularly during extended discharge periods.

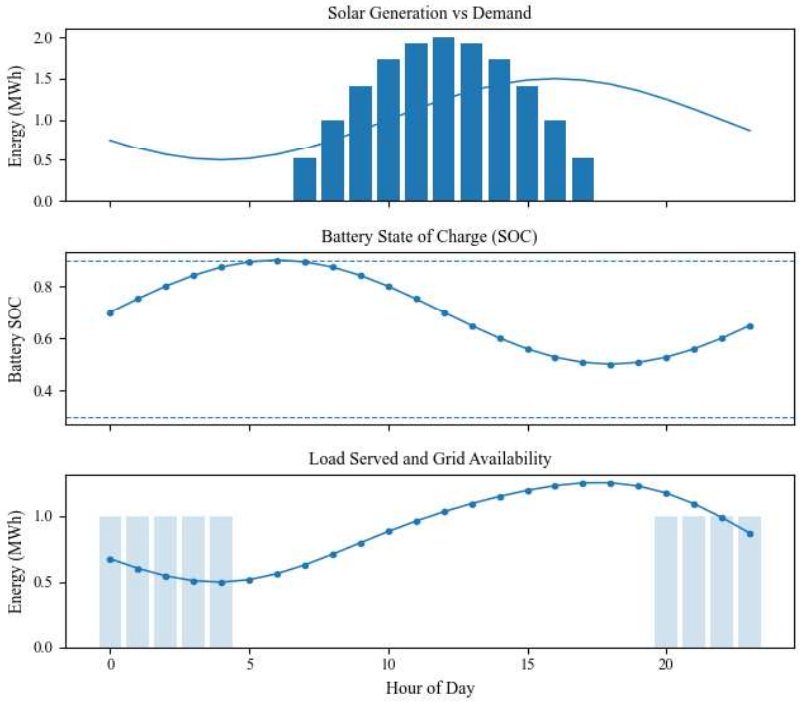

Figure 4: Solar Generation vs Demand, Battery State of Charge, Load Served and Grid Availability

Spatial aggregation effects represent the third limitation. The 60-node network representing Caibarién's approximately 1,800 users reduce local grid congestion issues. Figure 5 (top panel) illustrates this limitation: the combined load profile displays relatively smooth demand patterns, but actual neighborhood-level analysis would reveal local congestion during high solar export periods. This facilitates the study of electricity behavior at the neighborhood level, following logistics modeling principles (González Cabrera et al., 2025). However, this approach may not accurately measure voltage instability at distribution transformers during periods of high solar power production. This phenomenon has been observed in Cuban projects where more than 50% of electricity originates from solar panels (Oficina Nacional de Estadísticas de, 2024).

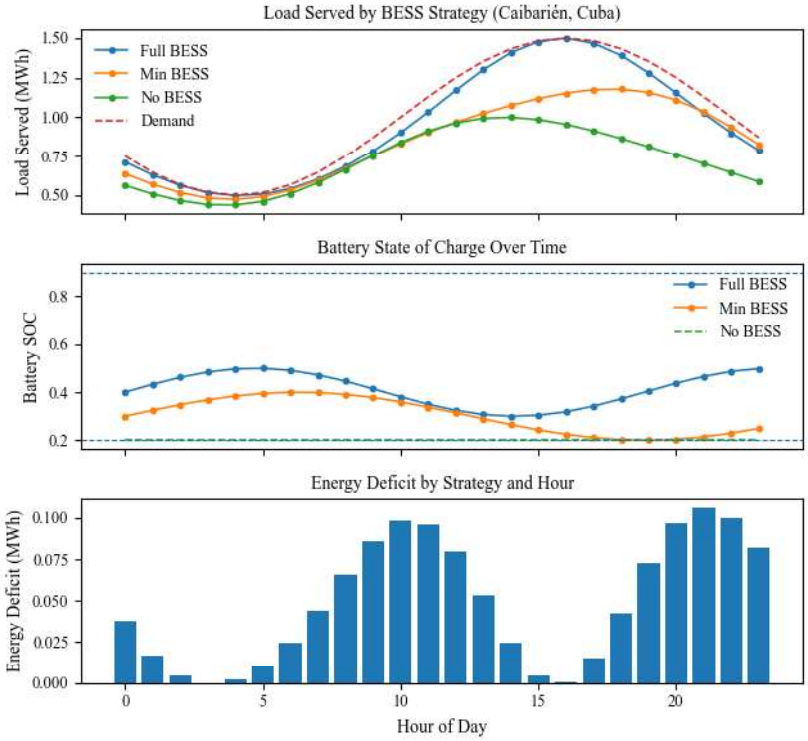

Figure 5: (Load Served by EMS Strategy, Battery State of Charge Over Time, Energy Deficit by Strategy and Hour)

Despite these limitations, the framework provides value by assisting municipal energy planners in decision-making processes. The deterministic approach offers a practical foundation for settings with limited resources. The framework also clearly demonstrates battery functionality and system performance (see Figures 5 and 6). This facilitates understanding for non-expert stakeholders regarding system operations.

3.5. Opportunities for Generalization and Transferability

The framework demonstrates applicability across multiple contexts. Figures 5 and 6 illustrate how the methodology can be adapted to different situations.

- Geographic Transferability: The framework architecture enables deployment across different locations. The binary grid availability constraint operates independently from geographic context; it requires only seasonal availability statistics as input. This facilitates rapid adaptation to other Caribbean Small Island Developing States by incorporating different outage patterns while maintaining the same optimization logic. Preliminary tests indicate that changes of ±10 percentage points in seasonal availability matrices alter optimal solar integration thresholds by less than 5 percentage points. This falls within the acceptable range for municipal planning. This indicates that the method can be applied in similar situations without major modifications, provided data regarding local outages and demand is available. Future research could validate this finding through comparative studies of other Caribbean municipalities.
- Sectoral Extensibility: Sectoral extensibility represents a property of logistics abstraction that remains independent of domain specificity. Figure 5 demonstrates how the five-phase structure can model energy deficit patterns for different strategies. Cross-domain validity reinforces the methodological claim that flow systems share fundamental logistical properties under disruption risk. The framework can model energy deficit by strategy and hour (see the bottom panel of Figure 5). This indicates applicability to other critical infrastructure systems where deficit management is essential.
- Policy Relevance: The framework generates actionable thresholds absent in traditional DSM literature, enhancing policy relevance. Figure 4 (middle panel) illustrates battery charge variation over time. This information supports decisions regarding battery sizing and utilization strategies. The dashed orange line at 0.3 State of Charge indicates battery utilization levels. This assists Cuban city planners in understanding achievable targets. Figure 5 (top panel) demonstrates how different energy management strategies affect energy satisfaction levels. These quantified thresholds represent a methodological advance over qualitative recommendations common in energy resilience literature (Diaz-Sarachaga et al., 2017); (United Nations Office for Disaster Risk Reduction, 2023).
- Compatibility with Existing Practices: The framework transferability is further enhanced by

compatibility with existing energy management practices. Figure 5 (middle panel) demonstrates how the framework integrates with standard Model Predictive Control approaches. This demonstrates that the logistics-energy integration approach can complement, not replace, existing methodologies. This compatibility facilitates adoption by municipal utilities already utilizing energy management systems. Implementation is streamlined, and enhanced protection against cyber-attacks is provided.

4. Limitations and Conclusion

4.1. Limitations

This study establishes a framework for integrating logistics and energy by redefining the concept of a "microgrid." Traditionally, a microgrid is defined as a local system that provides electricity to buildings. This study reconceptualizes the microgrid by treating electricity as a storable commodity that can be managed similarly to other logistical products. This method was applied in Caibarién, Cuba, a coastal town that experiences daily power outages exceeding 12 hours during the summer. The method identifies two specific implementation thresholds that are not mentioned in traditional literature on demand management: (i) At least 60% of solar energy is needed to ensure more than 80% resilience during the summer months, and (ii) at least 85% of people who produce and consume energy (prosumers) must use batteries for the system to function during long power outages. This is much higher than the 30–40% adoption rates considered sufficient in European studies that operate under stable grid conditions. These thresholds transform ideas about resilience into real technical details for city planners who do not have extensive resources.

Despite the contributions, three important limitations must be considered. First, the deterministic modeling approach, while facilitating mathematical calculations for municipalities without forecasting infrastructure, cannot capture the variability in outage duration. For example, it cannot account for outages that last 8 hours versus 16 hours within the same season. Second, assumptions about battery degradation (fixed 80% efficiency over the entire cycle) ignore the fact that there is an accelerated capacity loss (15–25% per year) in tropical climates. This could invalidate economic analyses extending beyond one year. Third, the data representation (60 nodes of approximately 1,800 end users) may underestimate localized voltage instability during periods of high solar export. These limitations create opportunities for future work: lightweight stochastic approximations that only require the average duration of outages, Arrhenius-based degradation models parameterized for Caribbean conditions, and hybrid modeling approaches that balance computational efficiency with engineering realism.

The methodology shows specific ways to use these resources in line with Cuba's National Renewable Energy Strategy for 2024 (Ministerio de Energía y Minas de Cuba, 2025). This tool supports decision-making processes. It uses Python to generate results that are independent of the solver and compatible with IT infrastructures that have limited resources. The Cuban provincial authorities in Villa Clara are interested in adapting it to plan for energy autonomy because the electricity grid is unstable. As a policy design tool, the quantified thresholds (60% integration, 85% battery adoption) provide data-driven targets for the design of subsidy programs under Cuba's duty-free import framework for residential photovoltaic systems.

Future research will improve the logistics-energy integration framework in three ways. It will start with specific applications and eventually become a general method for improving flow systems when there are risks of disruptions. Current efforts focus on creating a unified way to analyze flow systems that works for all three types of architecture:

- Centralized systems (one supply point with branches extending outwards)
- Hybrid systems (a central backbone with distributed generation and storage)
- Decentralized systems (peer-to-peer mesh networks with local autonomy)

This general plan will maintain the main five-phase structure (characterization → mathematical modeling → multi-criteria evaluation → risk and opportunity analysis → operational implementation) while adapting constraint formulations to specific physical domains. The goal is not just to apply it to different sectors, but to provide formal proof that flow systems, regardless of the physical medium, share basic optimization properties when operating under risk of supply disruption. This demonstrates that planning for critical infrastructure safety is connected to developing construction methods capable of addressing problems in regions worldwide.

4.2. Conclusions

This study offers five primary conclusions regarding the optimization of energy integration in vulnerable Caribbean contexts:

- Supply Chain Disruption Management: Modeling electricity as a storable commodity—with batteries serving as a safety net in case of grid unavailability—provides feasible solutions during extended blackouts (exceeding 12 hours). This is useful because conventional Demand Side Management (DSM) frameworks do not work during these times, as they assume that the grid will always be available.

- Quantitative Deployment Thresholds: Instead of using qualitative guidelines, quantitative deployment thresholds are utilized. The 60% solar integration minimum for greater than 80% summer resilience and greater than or equal to 85% battery adoption requirement among prosumers are engineering specifications for municipal planners to consider. These are not included in conventional DSM literature developed for stable grid contexts.
- Storage Density Viability: Storage density, not generation capacity, determines if a system is viable. All BA scenarios (5% battery adoption) were not possible during summer blackouts, regardless of solar energy usage. However, BF scenarios (100% adoption) were possible in all seasons. This shows that distributed storage is necessary, not optional, in situations where blackouts are common.
- Methodological Transferability: The five-phase framework successfully models different flow systems across contexts of vulnerability, which confirms that inventory theory is a unifying model for critical infrastructure resilience under disruption risk.
- Deterministic Tractability: The framework allows for use in settings with limited resources. It can be implemented by municipalities that lack advanced IT systems by using hourly demand profiles and binary grid availability matrices. It also generates evidence-based targets for subsidy programs. These targets are aligned with Cuba's renewable energy strategy. It makes it easier to deal with problems in the supply chain. Modeling electricity as a storable commodity—with batteries serving as a safety net in case of grid unavailability—provides feasible solutions during extended blackouts (>12 hours). This is useful because conventional DSM frameworks don't work during these times, as they assume that the grid will always be available.

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