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Research Article

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Posted Date: October 7th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-11269318/v1

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Additional Declarations: The authors declare no competing interests.

Resilience-Aware Multi-Objective Energy Management for Solar-Battery Microgrids Under Renewable Generation and Load Uncertainty

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Abstract
Solar battery microgrids face operational challenges caused by variable photovoltaic generation, changing electricity demand, battery limitations, and utility grid interruptions. This study develops a resilience aware multi objective energy management framework that coordinates photovoltaic generation, battery storage, utility exchange, flexible demand, and critical loads under grid connected and islanded conditions. The framework represents renewable and load variation through operating scenarios and jointly considers operating cost, battery degradation, renewable curtailment, energy not served, and critical load service. A controlled simulation using the IEEE 33 Bus Distribution System evaluates the framework over a 24 hour horizon with an 8 kWh battery and outage durations of two, four, and six hours. For the six hour outage, the proposed strategy reduces grid import from 11.92 kWh to 4.86 kWh and renewable curtailment from 8.58 kWh to 0.00 kWh. Critical load energy not served decreases from 9.57 kWh to 4.04 kWh, while critical load service increases from 74.11% to 89.07%. These results indicate that the framework can allocate limited energy toward critical demand during islanded operation while reducing renewable curtailment and grid dependence.

Keywords: Microgrid Energy Management; Multi Objective Optimization; Solar Photovoltaic; Battery Energy Storage; Renewable Energy Uncertainty; Critical Load Prioritization; Microgrid Resilience.

I. Introduction
The growing use of solar photovoltaic generation and battery energy storage is changing the operation of distribution systems. Solar battery microgrids can coordinate local generation, storage, flexible demand, and utility grid exchange within a common energy management system. However, variations in solar output and electricity demand, battery operating limits, and utility interruptions create complex scheduling conditions. Energy management therefore needs to consider operating cost, energy availability, and continuity of essential loads together.

Solar generation and electricity demand vary throughout the scheduling period, affecting local energy availability and battery operation. Battery storage can compensate for part of this variation, but its capacity, state of charge, power limits, and reserve requirements restrict available flexibility. During grid connected operation, utility import or export can support supply demand balance. During islanded operation, this support is unavailable, requiring coordinated use of photovoltaic generation, battery storage, and controllable demand. Previous studies have addressed stochastic energy management, battery storage, demand response, renewable uncertainty, and multi objective scheduling. However, the combined consideration of operating cost, battery use, renewable curtailment, energy not served, critical load service, and outage resilience remains an important research area.

This study addresses the coordinated scheduling of solar PV generation, battery storage, utility exchange, flexible loads, and critical loads under renewable variation, load changes, and grid interruption. The energy management system determines photovoltaic utilization, battery charging and discharging, grid import and export, flexible load scheduling, and load shedding subject to power balance, battery state of charge, charging and discharging limits, generation capacity, grid exchange limits, network conditions, and critical load requirements. Grid connected operation gives greater scope for economic scheduling and renewable utilization, while islanded operation requires greater priority for critical demand and battery reserves. A cost only objective therefore does not capture the complete operating problem.

This study proposes a resilience aware multi objective energy management framework for solar battery microgrids under variable renewable generation and load conditions. The framework integrates data preparation, uncertainty representation, microgrid modeling, multi objective optimization, outage simulation, and performance assessment. It coordinates photovoltaic generation, battery storage, utility exchange, flexible demand, and critical loads during grid connected and

islanded operation. The evaluation considers varying operating conditions and different outage durations, with emphasis on battery use, energy not served, renewable curtailment, and critical load service. The objective formulation considers operating cost, battery degradation cost, energy not served, renewable curtailment, and resilience related penalties subject to the physical and operating constraints of the microgrid.

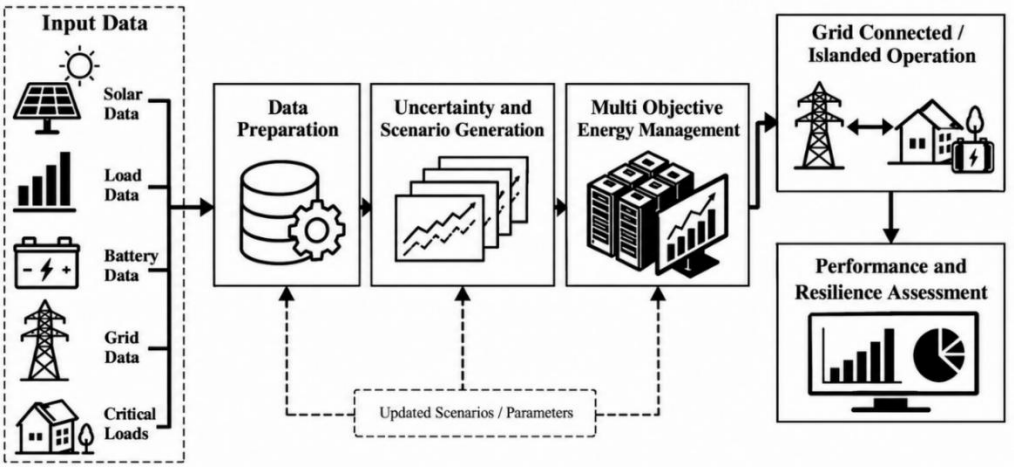


Fig. 1. Proposed resilience aware multi objective energy management framework for solar battery microgrids.

The framework provides a common structure for grid connected and islanded operation. During normal operation, photovoltaic generation, battery storage, flexible demand, and utility exchange are coordinated within their operating limits. During an outage, utility exchange is unavailable, critical loads receive higher service priority, and noncritical demand can be reduced when local energy is limited.

The main contributions are a multi objective energy management formulation that jointly considers operating cost, battery degradation, renewable curtailment, energy not served, and resilience. Renewable generation and load variation are represented through operating scenarios, while critical and noncritical loads are treated separately to prioritize essential demand during islanded operation. Photovoltaic utilization, battery charging and discharging, grid exchange, flexible demand, and load shedding are coordinated within a common scheduling framework. Resilience is evaluated across different outage durations using critical load service and critical load energy not served together with battery and energy management measures. The framework supports controlled simulation based evaluation with standardized distribution networks without requiring proprietary utility measurements. The remainder of this paper is organized as follows. Section II reviews previous studies on stochastic energy management, renewable energy and battery storage, renewable and load uncertainty, multi objective scheduling, demand response, and resilience oriented microgrid operation. Section III presents the proposed methodology, including the research framework, data preparation, uncertainty representation, microgrid modeling, multi objective optimization model, grid connected and islanded operation, and performance assessment procedure. Section IV presents the simulation results and discussion, including comparative energy management performance, critical load service under different outage durations, renewable curtailment, battery operation, and resilience related outcomes. Section V concludes the study by summarizing the main findings, limitations, and directions for future research.

II. Literature Review

Recent studies have examined microgrid operation under changing renewable output and electricity demand. Major areas include stochastic scheduling, battery storage, demand response, renewable integration, and multi objective optimization [1]–[7]. These studies provide the basis for developing an energy management approach that also considers service continuity during grid interruptions.

A. Stochastic Energy Management

Hajiamoosha et al. [1] presented a stochastic energy management method for renewable energy based microgrids with demand response. Their study shows how uncertain operating conditions can affect scheduling decisions. Hasankhani and Hakimi [2] examined a smart microgrid with intermittent renewable sources in an electricity market. Their results further support the use of stochastic methods when renewable output cannot be predicted with certainty.

B. Renewable Energy and Battery Storage

Eghbali et al. [3] studied renewable energy based microgrid scheduling with battery storage,

hydrogen storage, and demand response. The work shows the role of storage in handling variations in renewable supply and electricity demand. Duan et al. [4] considered photovoltaic, wind, and battery resources within a distribution network and applied multi objective optimization. Their study provides a useful basis for coordinating renewable sources and storage units during daily operation.

C. Renewable and Load Uncertainty

Variations in solar production and electricity demand can create difficulties for short term scheduling. Matamala and Feijoo [5] developed a two stage stochastic model with chance constraints for renewable generation uncertainty. Alobaidi et al. [6] examined decentralized energy management for unbalanced networked microgrids under uncertain conditions. These studies show the need to account for variations in available generation and demand when making operating decisions.

D. Multi Objective Scheduling

Microgrid scheduling normally involves several goals rather than a single target. Duan et al. [4] applied multi objective optimization to a renewable energy based microgrid with photovoltaic, wind, and battery resources. Karthik et al. [7] also examined multi objective optimization for microgrid energy scheduling. Such approaches provide a basis for considering economic operation together with other technical requirements.

E. Demand Response and Flexible Loads

Flexible demand can provide another option for balancing supply and demand. Hajiamoosha et al. [1] included demand response in stochastic microgrid scheduling. Eghbali et al. [3] combined demand response with battery and hydrogen storage. These findings indicate that controllable loads can work alongside storage resources when renewable generation changes during operation.

F. Resilience Oriented Operation

The reviewed studies address important aspects of microgrid scheduling, renewable generation, storage, uncertainty, and optimization [1]-[7]. However, the proposed study places greater emphasis on operation during utility interruptions. It considers critical load service, battery reserve levels, energy not served, renewable curtailment, and the ability of the microgrid to continue operating after separation from the main grid.

G. Research Gaps and Future Directions

The existing studies address individual parts of the problem, including stochastic scheduling [1], storage coordination [3], renewable uncertainty [5], decentralized operation [6], and multi objective scheduling [4], [7]. A combined treatment of operating cost, battery degradation, renewable curtailment, energy not served, critical load requirements, and outage resilience is less evident in the reviewed work. The interaction between uncertain solar generation, changing demand, battery state of charge, flexible loads, and critical loads also requires further study. The present study addresses these factors within a common optimization model. The framework coordinates photovoltaic output, battery charging and discharging, utility power exchange, flexible load scheduling, and load shedding under normal and disrupted conditions. The evaluation is conducted through controlled simulation using the IEEE 33 Bus Distribution System, with solar generation and electricity demand represented as simulation inputs. Future work can extend the evaluation to documented public solar and demand datasets and additional IEEE distribution systems, including the 69 Bus and 123 Bus systems. Larger scenario sets can also be used to examine different outage durations, battery capacities, demand levels, photovoltaic penetration levels, and critical load requirements.

III. Methodology

This study develops a resilience aware multi objective energy management framework for solar battery microgrids operating under renewable generation and load uncertainty. The method is designed for both grid connected and islanded operation. The overall process consists of data preparation, uncertainty generation, microgrid modeling, multi objective optimization, outage simulation, and performance validation. The main resources considered are solar photovoltaic generation, battery storage, utility grid exchange, flexible loads, and critical loads. The framework follows the research scope defined in the study, including renewable utilization, battery state of charge, energy not served, renewable curtailment, and resilience assessment.

A. Research Framework and System Architecture

The proposed framework is organized as a sequential process. First, solar generation and electricity demand profiles are prepared for controlled simulation. The selected data are then cleaned and converted into time synchronized profiles. The resulting profiles are used to represent normal operating conditions and uncertain scenarios. The next stage represents the microgrid through its main operational components. Solar photovoltaic generation supplies available renewable power, while the battery provides charging and discharging flexibility. The utility connection permits power import or export during grid connected operation. Flexible loads can be shifted or reduced when required, while critical loads receive a higher service priority. The

optimization layer receives the renewable generation scenarios, load scenarios, battery conditions, grid status, and load priorities. It then determines photovoltaic utilization, battery charging and discharging, utility exchange, flexible load scheduling, and load shedding. These decision variables are consistent with the optimization formulation proposed in the document.

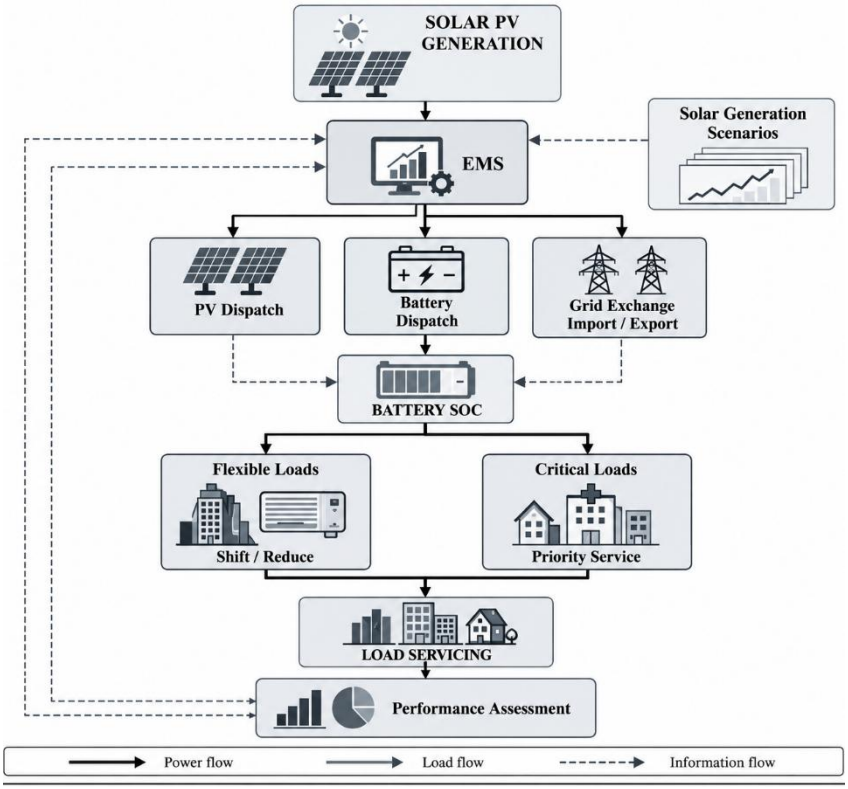


Fig. 2. System architecture of the proposed solar battery microgrid energy management framework.

B. Data Collection and Preparation

The study does not require proprietary utility data, physical microgrid measurements, or a documented public time series for the reported case study. The IEEE 33 Bus Distribution System is used as the standardized network test system. Solar generation and electricity demand profiles are represented as simulation inputs to evaluate renewable variability, battery operation, grid exchange, flexible demand, critical load service, and outage response. The prepared inputs contain time indexed solar generation, electricity demand, battery parameters, grid operating conditions, and network parameters. Data preparation includes checking incomplete records, correcting invalid values, synchronizing solar and load time intervals, and converting the inputs into consistent units. The same input conditions are applied to the conventional and proposed strategies to provide a consistent basis for comparison.

Table I. *Data Inputs and Processing Procedure*

Data category	Main variables	Processing
Solar generation	PV output, available PV power	Missing value check, unit conversion, time synchronization
Electricity demand	Total load, flexible load, critical load	Missing value check, scaling, time synchronization
Battery	Initial state of charge, capacity, charge and discharge limits	Parameter validation
Utility grid	Import limit, export limit, grid availability	Operating state coding
Distribution network	Bus, line, voltage, and power flow parameters	IEEE test system configuration
Outage scenarios	Outage state, duration, affected operating period	Defined outage cases

C. Uncertainty Representation and Scenario Generation

Solar generation and electricity demand are treated as variable inputs during the scheduling horizon. The framework represents changes in renewable availability and electricity demand rather than

relying on a single fixed operating condition. Solar profiles are used to represent variations in available photovoltaic power, while demand profiles represent changes in total, flexible, and critical loads. Outage conditions are introduced to examine system operation during temporary loss of utility supply. The evaluation considers outage durations of 2 hours, 4 hours, and 6 hours. Each case is evaluated under the same system configuration so that changes in battery operation, energy not served, renewable curtailment, and critical load service can be compared across operating conditions.

D. Microgrid Modeling

The microgrid model contains five principal operating elements: photovoltaic generation, battery storage, utility grid exchange, flexible loads, and critical loads. The photovoltaic unit supplies renewable energy up to its available generation level. When solar production exceeds immediate demand and battery charging capability, the remaining energy can be curtailed. During periods of insufficient solar production, the battery or utility grid can supply the deficit. The battery is represented through its state of charge. Charging increases stored energy, while discharging reduces the available stored energy. Charging and discharging limits are imposed so that the battery remains within its permitted operating range. The battery also maintains a reserve during islanded operation so that critical loads can continue receiving power. Flexible loads can be shifted or reduced according to the scheduling decision. Critical loads are treated separately because their service requirement is higher than that of flexible demand. Load shedding is therefore applied first to noncritical demand when available generation is insufficient. The utility grid has two operating states. In grid connected mode, the microgrid can import or export power within the specified exchange limits. During an outage, grid exchange is set to zero and the system operates in islanded mode.

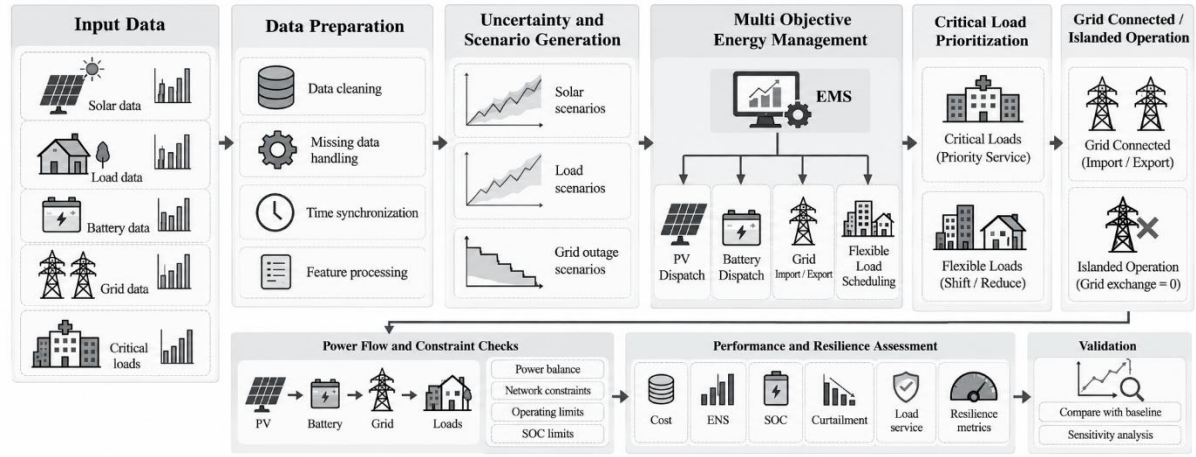


Fig. 3. Data flow and decision process for resilience aware multi objective microgrid energy management.

E. Multi Objective Optimization Model

The central part of the proposed method is the multi objective optimization model. The optimization simultaneously considers economic operation, battery usage, renewable curtailment, unserved energy, and resilience. These objectives are directly derived from the research formulation provided in the document.

The main objective function is formulated as:

$$J = w_1 C_{op} + w_2 C_{deg} + w_3 C_{ENS} + w_4 C_{curt} + w_5 C_{res}$$

Where, (C_{op}) represents operating cost, (C_{deg}) represents battery degradation cost, (C_{ENS}) represents the penalty associated with energy not served, (C_{curt}) represents renewable energy curtailment, and (C_{res}) represents the resilience related penalty. The coefficients (w_1) through (w_5) define the relative importance of the five objectives. They satisfy $w_i \geq 0$ and $\sum_{i=1}^{5} w_i = 1$. The formulation therefore uses five objective weights, consistent with the five terms in the objective function.

For the reported outage cases, the resilience penalty is defined as the normalized critical load energy not served during the outage:

$$C_{res} = \frac{E\,NS_{critical}, out}{E^{demand}_{critical,out}}$$

Here, $C_{res} = 0$ indicates full critical load service, while larger values indicate greater critical load interruption. This definition makes the resilience term consistent with the critical load ENS and critical load service metrics reported in the results.

The operating model must also satisfy power balance during every scheduling interval. The basic balance equation is:

$$\boldsymbol{P_{PV,t} + P_{dis,t} + P_{imp,t} = P_{nc,t} + P_{crit,t} + P_{ch,t} + P_{curt,t} + P_{exp,t}}$$

Where, $\boldsymbol{P_{PV,t}}$ is utilized photovoltaic power, $\boldsymbol{P_{dis,t}}$ is battery discharge, $\boldsymbol{P_{imp,t}}$ is grid import, $\boldsymbol{P_{nc,t}}$ is served noncritical demand, $\boldsymbol{P_{crit,t}}$ is served critical demand, $\boldsymbol{P_{ch,t}}$ is battery charging power, $\boldsymbol{P_{curt,t}}$ is curtailed photovoltaic power, and $P_{exp,t}$ is grid export.

Flexible demand is therefore modeled as part of the noncritical demand rather than as an independent power source. This avoids the inconsistency present in the earlier formulation. Grid import and export are also represented as separate nonnegative variables, which removes ambiguity in the sign of grid exchange. The optimization is subject to photovoltaic availability, battery SOC limits, charging and discharging limits, grid exchange limits, network operating limits, and critical load service requirements. The optimization is evaluated over a 24 hour scheduling horizon with hourly time intervals. The selected IEEE 33 Bus Distribution System is used as the network test case. The battery energy capacity is set to 8 kWh, with a maximum charging power of 3 kW and a maximum discharging power of 3 kW. The charging and discharging efficiencies are both set to 95%, and the initial battery state of charge is set to 50%. An islanding event is introduced at hour 18 and maintained for six hours. The same system configuration and operating conditions are applied to the conventional and proposed strategies for comparative evaluation. The optimization considers photovoltaic utilization, battery charging and discharging, grid import and export, flexible load scheduling, and load shedding while accounting for the defined operating constraints.

F. Grid Connected and Islanded Operation

During grid connected operation, photovoltaic generation, battery storage, flexible demand, and utility exchange are coordinated according to the selected operating objectives. Excess renewable generation can be stored, exported to the utility grid, or curtailed when charging and export capacity are limited. When a utility outage occurs, grid import and export are set to zero and the microgrid enters islanded operation. Available photovoltaic generation, battery storage, and controllable demand are then coordinated to supply the local load. Critical loads receive higher priority, while noncritical flexible demand can be reduced when available power is insufficient. Battery energy is allocated according to the load priorities and the remaining outage period.

G. Validation and Performance Assessment

The proposed framework is evaluated through controlled scenario based simulation using the IEEE 33 Bus Distribution System. The assessment compares the conventional and proposed strategies under the same solar generation, demand, battery, grid, and outage conditions. The evaluation considers power balance, battery operation, grid exchange, renewable curtailment, total energy not served, critical load energy not served, critical load service, and operating cost. Resilience is assessed through the ability to maintain critical load service during utility interruption. Outage duration is varied across the defined scenarios to examine changes in critical load service and energy not served. The results are compared across the conventional and proposed strategies to identify the operational tradeoff between overall load service and priority based critical load protection.

H. Reproducibility Procedure

The analysis follows a fixed sequence consisting of data preparation, network configuration, uncertainty representation, microgrid state definition, optimization, constraint checking, and performance calculation. The same system configuration, operating parameters, outage conditions, and evaluation criteria are applied to the conventional and proposed strategies. The simulation results are then compared using grid exchange, battery operation, renewable curtailment, energy not served, critical load service, and operating cost. This procedure provides a consistent basis for repeating the evaluation with the selected test system and input profiles.

IV. Results and Discussion

This section presents the simulation results for the conventional and proposed energy management strategies under grid connected and islanded conditions. The analysis focuses on energy use, critical load service, renewable curtailment, and performance under different outage durations.

A. Results

The proposed resilience aware multi objective energy management framework was evaluated under grid connected and islanded operating conditions. The simulation considered photovoltaic generation, battery storage, utility grid exchange, flexible demand, critical load prioritization, renewable curtailment, and load shedding. A 24 hour operating horizon was considered with an 8 kWh battery, a maximum charging and discharging power of 3 kW, charge and discharge efficiency of 95%, and an initial state of charge of 50%. The islanding event was introduced at hour 18 and continued for six hours. Critical load service was prioritized through the critical load constraints and resilience formulation. The reported numerical results represent a controlled simulation case study rather than measurements collected from a physical microgrid.

Table II compares the conventional dispatch strategy with the proposed resilience aware strategy. The proposed strategy reduces grid import from 11.92 kWh to 4.86 kWh, corresponding to a reduction of approximately 59.2%. At the same time, grid export increases from 0.00 kWh to 8.58 kWh. This change indicates a different treatment of surplus photovoltaic generation under the proposed scheduling structure. Instead of curtailing surplus renewable energy, the model coordinates battery operation and grid exchange so that a larger proportion of available photovoltaic generation can be utilized or exported.

Table II. *Comparison of Conventional and Proposed Energy Management Strategies*

Performance Metric	Conventional Strategy	Proposed Strategy
Grid import (kWh)	11.92	4.86
Grid export (kWh)	0.00	8.58
Battery charging (kWh)	8.58	6.32
Battery discharging (kWh)	7.98	8.96
Renewable curtailment (kWh)	8.58	0.00
Total ENS (kWh)	17.40	21.97
Critical load ENS (kWh)	9.57	4.04
Critical load service (%)	74.11	89.07
Operating energy cost, relative simulation cost	3.10	1.10

The proposed strategy records a higher total energy not served than the conventional strategy, increasing from 17.40 kWh to 21.97 kWh. However, critical load energy not served decreases from 9.57 kWh to 4.04 kWh, while critical load service increases from 74.11% to 89.07%. This difference results from the priority assigned to critical demand during the outage period. When available generation and stored battery energy are limited, the proposed strategy allows a greater portion of noncritical demand to remain unserved so that more energy can be directed toward critical loads. The result therefore reflects a tradeoff between total load service and priority based resilience management. The battery results provide further information about the scheduling behavior. Battery charging decreases from 8.58 kWh under the conventional strategy to 6.32 kWh under the proposed strategy, while battery discharge increases from 7.98 kWh to 8.96 kWh. This pattern is consistent with the proposed reserve oriented operation. The battery is treated as an energy resource that must support the islanded period rather than as a resource for short term energy balancing alone. The optimization therefore changes the timing and purpose of battery use across the scheduling horizon. Renewable curtailment decreases from 8.58 kWh to 0.00 kWh. The result indicates that the proposed scheduling structure can use available photovoltaic generation through coordinated battery charging, local demand supply, and grid export. This is relevant to solar dominated microgrids because periods of high photovoltaic output can create surplus generation when local demand is comparatively low. The result also illustrates the interaction between renewable utilization and battery scheduling within the multi objective formulation. The total energy not served increases from 17.40 kWh to 21.97 kWh. This result requires interpretation in relation to the load priority structure. The proposed model does not attempt to minimize total interruption without considering load type. Instead, it gives greater protection to critical demand and permits a larger share of noncritical demand to be interrupted during islanded operation. Consequently, critical load ENS decreases from 9.57 kWh to 4.04 kWh, representing an approximate reduction of 57.8%. Critical load service also increases from 74.11% to 89.07%.

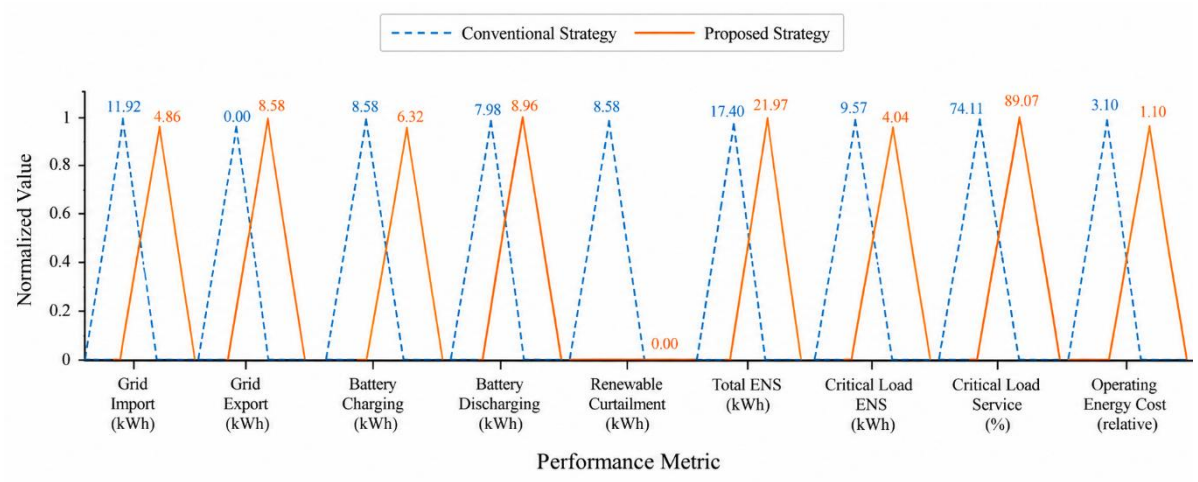


Fig. 4. Normalized comparison of key performance metrics between conventional and proposed strategies.

The proposed strategy reduces grid import and renewable curtailment while improving critical load service. The reduction in critical load ENS also indicates that the proposed strategy gives greater priority to critical demand during the outage period.

The energy cost results show a reduction in the relative simulation cost from 3.10 under the conventional strategy to approximately 1.10 under the proposed strategy. These values represent the defined simulation cost structure rather than actual retail electricity tariffs. Therefore, the result should be interpreted as a comparison between the two scheduling strategies under identical simulation assumptions rather than as a direct estimate of monetary savings for a physical microgrid. Battery state of charge provides a direct indication of the reserve strategy. At the beginning of the six hour islanding period, the proposed optimization maintains approximately 7.60 kWh of stored energy, corresponding to 95% of the 8 kWh battery capacity. The terminal state of charge reaches approximately 1.60 kWh at the end of the simulated horizon. This operating pattern indicates that a substantial portion of stored energy is retained for the islanded period. During grid connected operation, the battery absorbs part of the available photovoltaic surplus and supplies demand deficits. During islanded operation, discharge is coordinated with load priority so that critical demand receives greater protection. The reserve strategy becomes particularly important for the six hour outage because grid support is unavailable throughout the islanded period. As stored energy becomes limited, the optimization permits greater interruption of noncritical demand while preserving service to critical demand. This behavior is consistent with the objective structure defined in the methodology, where critical load continuity and resilience are considered alongside operating cost, battery use, energy not served, and renewable curtailment.

Table III presents the results for two hour, four hour, and six hour outage events. The outage begins at hour 18 for each case. Critical load service under the proposed strategy is 100.00% for the two hour event, 93.53% for the four hour event, and 89.07% for the six hour event. The corresponding critical load ENS values are 0.00 kWh, 2.39 kWh, and 4.04 kWh.

Table III. *Resilience Performance Under Different Outage Durations*

Outage Duration	Strategy	Total ENS (kWh)	Critical Load ENS (kWh)	Critical Load Service (%)
2 h	Conventional	4.30	2.37	93.60
2 h	Proposed	17.93	0.00	100.00
4 h	Conventional	11.90	6.55	82.29
4 h	Proposed	20.31	2.39	93.53
6 h	Conventional	17.40	9.57	74.11
6 h	Proposed	21.97	4.04	89.07

The results show a clear relationship between outage duration and critical load service. As outage duration increases, critical load service under the proposed strategy decreases from 100.00% to 93.53% and then to 89.07%. The decline is associated with the finite battery capacity and the

absence of grid support during islanded operation. Nevertheless, the proposed strategy maintains a higher critical load service level than the conventional strategy at all three outage durations .

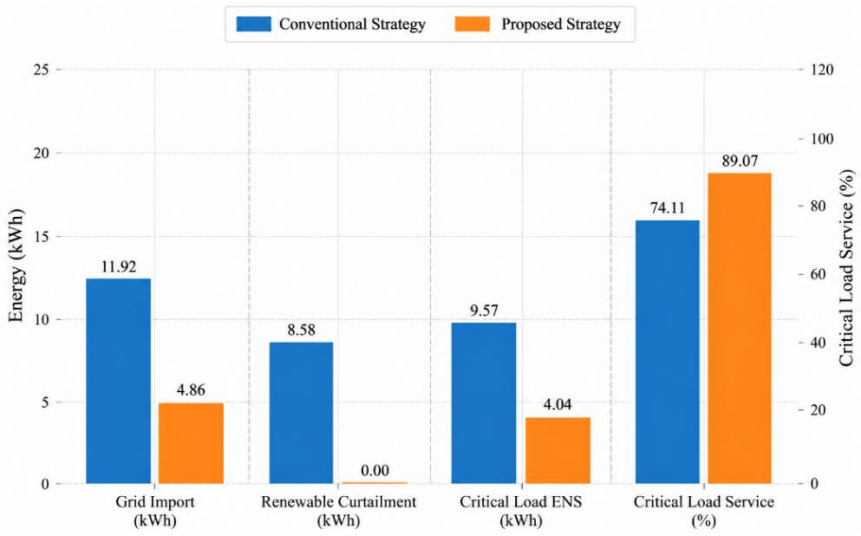


Fig. 5. Direct comparison of grid import, renewable curtailment, critical load ENS, and critical load service.

The proposed strategy reduces grid import and renewable curtailment while improving critical load service. It also lowers critical load ENS from 9.57 kWh to 4.04 kWh, indicating stronger protection of critical demand.

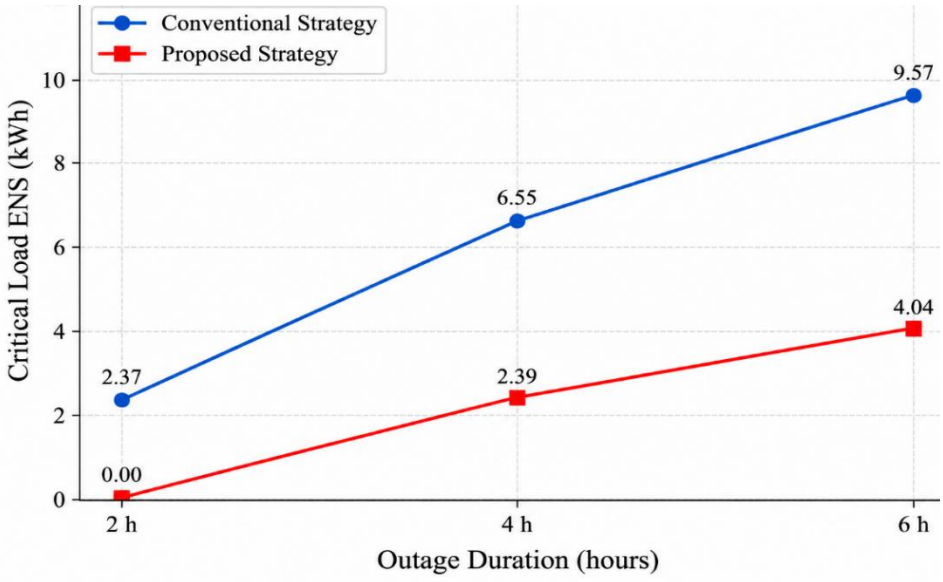


Fig. 6. Critical load ENS under different outage durations for the conventional and proposed strategies.

Figure 6 shows the critical load ENS for the two, four, and six hour outage cases. The proposed strategy maintains lower critical load ENS across all outage durations, with the difference becoming more visible as outage duration increases.

B. Discussion

The results show that the proposed strategy changes energy allocation from short term balancing toward coordinated economic and resilience oriented operation. Grid import decreases from 11.92 kWh to 4.86 kWh, while renewable curtailment falls from 8.58 kWh to 0.00 kWh. At the same time, battery discharge increases from 7.98 kWh to 8.96 kWh and grid export reaches 8.58 kWh, indicating greater use of stored and surplus photovoltaic energy.The main resilience effect appears in critical load protection. Critical load ENS decreases from 9.57 kWh to 4.04 kWh, while critical load service increases from 74.11% to 89.07% during the six hour outage. This improvement is achieved through greater allocation of available energy to critical loads, with more

noncritical demand remaining unserved when resources become limited. The outage duration results support this behavior, with critical load service decreasing from 100.00% for two hours to 93.53% for four hours and 89.07% for six hours as the available battery energy becomes more constrained. The increase in total ENS from 17.40 kWh to 21.97 kWh should therefore be interpreted together with the critical load results. The proposed strategy accepts greater interruption of noncritical demand to reduce interruption of essential demand. This shows why total ENS alone is insufficient for assessing resilience when loads have different priorities. Critical load ENS and critical load service provide additional measures of how available energy is allocated during islanded operation. The relative simulation cost also decreases from 3.10 to 1.10, while renewable curtailment falls to zero. These values depend on the simulation assumptions and cost coefficients and should not be interpreted as direct electricity tariff savings. Overall, the results show that economic operation, renewable utilization, battery use, and critical load protection can be evaluated within the same energy management framework.

C. Limitations and Future Work

The study has several limitations. First, the evaluation is based on controlled simulation rather than measurements from a physical microgrid. Second, the analysis uses a single 24 hour horizon, an 8 kWh battery, and a six hour outage, which limits coverage of different system conditions. Third, the uncertainty analysis uses a limited set of outage cases rather than larger scenario sets with documented public time series. Future work should test the framework with public solar and demand datasets and multiple IEEE distribution systems, including the 33 bus, 69 bus, and 123 bus systems.

V. Conclusion

This study developed a resilience aware multi objective energy management framework for solar battery microgrids under renewable generation variation, load changes, and utility interruptions. The framework coordinates photovoltaic generation, battery storage, grid exchange, flexible demand, and critical load priorities within grid connected and islanded operation. The simulation results show that the proposed strategy reduced grid import from 11.92 kWh to 4.86 kWh and renewable curtailment from 8.58 kWh to 0.00 kWh. Critical load ENS decreased from 9.57 kWh to 4.04 kWh, while critical load service increased from 74.11% to 89.07% during the six hour outage. Across the outage cases, critical load service remained at 100.00% for two hours, 93.53% for four hours, and 89.07% for six hours. These results show that the proposed scheduling approach directs limited energy toward critical demand during islanded operation. The increase in total ENS from 17.40 kWh to 21.97 kWh indicates a tradeoff between overall load service and critical load protection. The results therefore support the use of critical load ENS and critical load service alongside total ENS when assessing microgrid resilience. The study is based on controlled simulation rather than physical microgrid measurements. Future work should test the framework with documented public solar and demand datasets, multiple IEEE distribution systems, larger scenario sets, and different battery and outage conditions. Comparative evaluation of different optimization methods can also provide further evidence of the framework's performance across varied microgrid configurations.

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