Community-Aware Reliability Metrics for Strategic Battery Storage Placement in Distribution Systems

Fredrica Arthur
Electrical and Computer Engineering Department
Louisiana State University
Baton Rouge, USA
farthu1@lsu.edu

Farshad Amani
Electrical and Computer Engineering Department
Louisiana State University
Baton Rouge, USA
famani1@lsu.edu

Amin Kargarian
Electrical and Computer Engineering Department
Louisiana State University
Baton Rouge, USA
kargarian@lsu.edu

Frederick Weil
Department of Sociology
Louisiana State University
Baton Rouge, USA
fweil@lsu.edu

***Abstract*—Traditional power system reliability metrics, such as energy not supplied (ENS), are predominantly utility-centric, focusing on system-wide performance while overlooking the disproportionate impacts of power outages on low-income households. Although the classical ENS metric provides significant insight for grid reliability analysis, it does not address socioeconomic disparities. This paper introduces a community-aware reliability metric that incorporates community hardships into the reliability assessment of power distribution systems. Through a preliminary survey study, three socioeconomic factors, including income, education, and homeownership, are identified to measure community hardships caused by power failures. These factors are combined to create a hardship index for each community zone, which is then integrated with ENS to develop a combined community-utility reliability index. As proof of concept, this reliability index has been applied to the placement of battery storage to establish a community-aware decision-making framework. This framework considers both utility and community needs in storage placement. Simulation results on a 13-bus power distribution system demonstrate that community-aware placement reduces hardship-weighted ENS in low-income households by 43.9%, significantly addressing socioeconomic inequities while maintaining acceptable system-wide reliability that meets both technical and social objectives.**

***Index Terms*—Reliability, energy not supplied, community hardship, community-utility reliability metric, energy storage placement.**

I. INTRODUCTION

Various reliability metrics have been used over the past several decades to measure and improve power system reliability. Prevalent methods have focused on finding optimum solutions that result in improved technical and system performance using metrics such as energy not supplied (ENS), system average interruption duration index, system average interruption frequency index, and customer average interruption duration index. The forefront has been to improve performance from the utility's point of view [1], [2].

ENS stands out as a metric that provides a broader perception of the impact of outages beyond the sum of interruption frequency and duration. ENS is critical in measuring total unsupplied energy due to outages, enabling utilities to understand the overall impact caused by grid interruptions. High ENS values indicate systemic weaknesses, such as aging infrastructure or insufficient maintenance. This metric is relevant for regions exposed to natural disasters, where prolonged outages sharply increase ENS values [3]. However, this metric does not capture the socioeconomic vulnerabilities at the community level in low-income households; therefore, it overlooks the disparate burden of outages in such areas.

Low-income households are often situated in geographic areas of disadvantage where natural disasters can cause severe damage, increasing the risk of unreliable power [4], [5]. During Hurricane Ida, 91 deaths were recorded, of which 17 (18.7%) were caused by extended power outages in low-income households [6]. Such areas are prone to system failures, where infrastructure elements such as poles and transformers have long exceeded their estimated useful life. The grid infrastructure in high-income households is generally modern and reliable, while low-income households with old infrastructure usually experience more extended restoration than initially planned [7]. Targeted solutions such as distributed renewable energy [8], [9], [10], battery energy storage system (BESS) [11], and community-driven energy models can address these disparities and improve reliability.

BESS plays a key role in enhancing power system reliability by offering critical backup and ensuring balance in power supply during periods of outage [12]. BESS reduce peak demand charges, significantly benefiting low-income households [13]. The deployment of BESS provides reliable and sustainable energy solutions that improve energy equity.

Recent studies have emphasized the need and importance

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of integrating the concepts of equity and community energy needs into power system problems, including various decision-making approaches [14], [15], [16]. For example, recent work by Luis et al. [17], [18] presents an equity-aware approach to integrate equity in restorative actions after extreme events. Miguel et al. [19] present an equitable energy intervention quantitative framework. A multi-objective optimization model is described to minimize the energy burden of energy-insecure households. These studies depict the prioritization of low-income households but lack community hardship measurement, definition of reliability equity metrics, and their integration into infrastructure planning problems such as storage placement.

This paper proposes a novel community-aware reliability metric which integrates community hardship, quantified through socio-economic factors such as income, education, and homeownership, into the traditional ENS framework. Key contributions of this paper include: a hardship-weighted ENS metric, which combines technical performance and socio-economic considerations; an equity-driven energy storage placement framework, prioritizing low-income households. The proposed framework presents a trade-off between utility-centric and community-aware strategies and ensures that the benefits of modern energy solutions reach low-income households through an equity-aware battery storage placement approach.

II. Problem Definition

Reliability metrics play a central role in various decision-making approaches and tools. However, traditional metrics often fail to account for the socioeconomic disparities across communities. Research has shown that the impact of power outages disproportionately affects low-income regions, where vulnerabilities are significantly higher [20]. The loss of kilowatt-hours in high-income households cannot be equated to the same loss in low-income households [21]. This underscores the need for reliability evaluation metrics that not only reflect utility performance but also consider the broader impact on communities.

This paper addresses the problem of integrating community hardships into the ENS reliability metric and applying it for informed decision-making. The first step involves identifying and quantifying community hardships resulting from power outages. To this end, a preliminary survey was conducted to collect data through targeted questions. While the ultimate goal is to extend this survey to collect data from communities in New Orleans, the initial survey involved hundreds of Louisiana State University students, along with input from their families and friends.

The collected data was analyzed to identify key factors that influence community hardship. These factors were then modeled mathematically and incorporated into the ENS metric to create a hardship-weighted ENS framework. This enhanced metric forms the foundation of a decision-making analysis, which we have applied to evaluate battery storage placement in power distribution systems. The objective of this framework is two-fold: to improve system reliability and to alleviate community hardships caused by power outages.

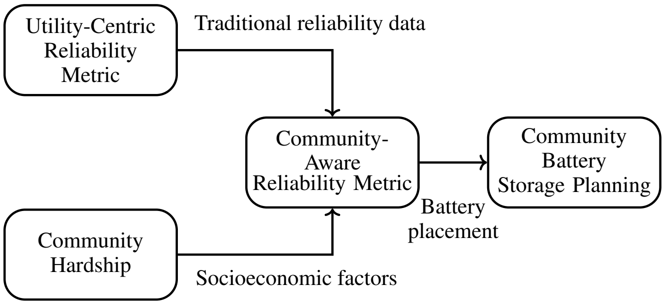

Fig. 1. Proposed framework for community-aware reliability metric with battery storage.

III. Proposed Community-Aware Reliability Assessment

This section provides a detailed explanation of the proposed community-aware reliability assessment. An overview of the proposed framework is presented in Fig. 1. A traditional reliability metric, ENS, is combined with community hardship factors that account for both grid technical perspectives and community hardship due to power outages.

A. Utility Centric ENS Metrics

In conventional power systems, reliability indices are calculated within a given system configuration [13]. ENS is a major determinant of the system's overall performance, which offers a critical measure of the energy impact.

$$\mathrm{ENS} = \sum_i \mathrm{La}_i \times \mathrm{U}_i \tag{1}$$

where La_i represents the average load on bus i, and U_i denotes the annual power outage duration at bus i, measured in hours per year. The summation over all buses i accounts for the total ENS across all load points.

While ENS is useful in evaluating the overall reliability of a system, many shortcomings exist in quantifying specific community-level impact. The major problem is that it limits the ability to accurately represent variability within geography. The same applies to other reliability metrics. All these utility-centric indices define reliability from a grid perspective and primarily do not consider geographic or community-level variations in outage frequency and duration.

B. Community-Aware Reliability Metric

Through a preliminary survey conducted by Louisiana State University students, our initial study identified certain hardships Gulf Coast residents of Baton Rouge and New Orleans experience during prolonged power outages. Power outages in these areas were determined to pose community challenges, such as economic instability, social isolation, and health risks. People without comfortable alternative transportation resort to staying in their homes without electricity. Through the study, three main socioeconomic factors are identified as necessary to quantify community hardship weights in a nuanced measure for low-income households. These include education, income, and homeownership and are discussed in more detail below.

a) Education: High educational attainment is often associated with better job opportunities and effective use of energy consumption. However, in areas with lower levels of education, people find it harder to access energy programs and resources that could help them prepare for power outages.

b) Household Income: A community's income level indicates its ability to pay for and manage energy services during disruption. Low-income households are more at risk of energy poverty, where an abnormally high portion of household budgets is spent on energy.

c) Homeownership: Higher homeownership rates indicate more stable energy demand, while low rates indicate transient populations or a preponderance of rental housing. Percent owner-occupied housing provides a sense of vulnerability in any area.

Combined Community-Utility Reliability Metric: Consider a power distribution system composed of multiple community zones. To develop a more community-focused reliability metric, we enhance the traditional utility-centric energy not supplied metric. We calculate the ENS for each community zone and aggregate these values into a weighted ENS index, Ω_{ENS}, for the entire power distribution system, as defined in (2).

$$\Omega_{\text{ENS}} = \sum_{\forall z} \text{ENS}_z \times \omega_z \tag{2}$$

where the energy not supplied for each community zone z is represented as ENS_z and is defined as:

$$\text{ENS}_z = \sum_{i \in L_z} \text{La}_i \times \text{U}_i \tag{3}$$

The community ENS_z is the product of the average load La_i and the duration of annual power outage U_i at each load point in the community zone z.

In (2), ω_z represents a socioeconomic weighting factor that quantifies the hardships experienced by zone z due to power outages. This factor is applied to ENS_z to create a weighted ENS index, Ω_{ENS}, which integrates both the technical aspects of the power grid and the socioeconomic challenges faced by each community zone. The socioeconomic weight for each zone incorporates three key factors, i.e., education, income, and homeownership, and is calculated as follows:

$$\omega_z = \omega_i \left(\frac{\text{AI}}{\text{AI}_z}\right) + \omega_e \left(\frac{\text{AE}}{\text{AE}_z}\right) + \omega_h \left(\frac{\text{AH}}{\text{AH}_z}\right) \tag{4}$$

ω_z represents the composite socioeconomic weight for each zone, where each term compares the socioeconomic status of a community with the averages in the system explained below:

- ω_i: relative weight for income, calculated by comparing the average income (AI) of all communities to that of a particular community zone (AI_z).
- ω_e: relative weight for education, compares the average education level (AE) across all communities to a particular community zone (AE_z).
- ω_h: relative weight for homeownership, compares the average value (AH) across all communities to a particular community zone (AH_z).

C. Benefits of Proposed Community-Aware Reliability Metric

- Sensitivity to Disparities: Unlike traditional metrics, Ω_{ENS} points out areas where power supply failure is most frequent and suggests improvements where socioeconomic weights are maximal.
- Promotes Energy Equity: The metric aligns with the energy equity goals in addressing energy reliability inequities, providing higher hardship weights for at-risk areas.
- Smart Decision Making: Promoting smart decision-making in policymaking, focusing on improving reliability in areas requiring it most.
- Attention to Community Requirements: It enables a community-driven approach to energy reliability for sustainable and equitable development.

D. Community-aware Storage Planning

As proof of concept, we consider a battery energy storage system placement problem for improving the reliability of the power distribution system. Beyond improving overall grid reliability, strategically placing BESS can help address energy disparities by prioritizing low-income households, thus reducing inequalities in storage planning [13].

Unlike traditional decision-making approaches that rely on the utility-focused ENS metric for battery placement, we use the proposed community-utility weighted ENS index Ω_{ENS} to identify the optimal locations for energy storage systems. This hardship-weighted ENS metric prioritizes areas with the greatest needs, guiding the placement of BESS to reduce outage frequency and ensure critical services are maintained in vulnerable communities.

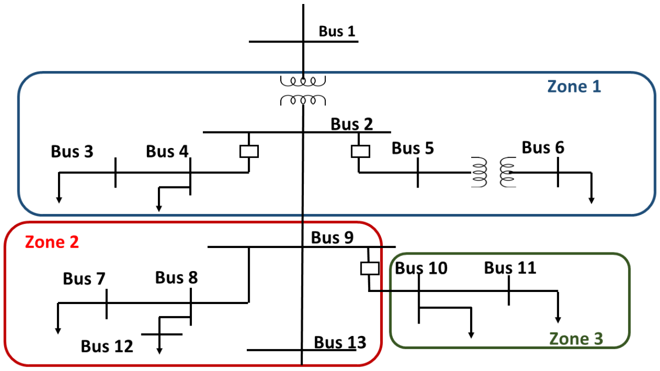

Fig. 2. 13-bus distribution system divided into three zones based on socioeconomic characteristics. Zone 1 (blue), Zone 2 (red), and Zone 3 (green) represent middle-income communities, most vulnerable communities, and affluent communities, respectively.

IV. CASE STUDY

BESS placement strategies were evaluated using an unbalanced 13-bus distribution system, modeled and analyzed in ETAP software. Simulation-based evaluations of different placement strategies were conducted to show their impacts on system reliability which provide information on technical and socioeconomic considerations. As shown in Fig. 2, the system is divided into three distinct zones, each representing communities that reflect the unique socioeconomic characteristics. Hardship weights (ω_z) were derived using (4) which combines relative weights arbitrarily assigned. (ω_i) had a strong impact in quantifying hardship index, hence was assigned the highest weight (0.5). (ω_e) was assigned a value (0.3) due to its moderate impact in calculating the hardship index. Lastly, (ω_h) had the least impact on quantifying the hardship index and was therefore assigned the lowest value (0.2). These relative weights sum up to 1 and are apportioned according to the relative impact in measuring hardship index. Tables I and II show the socioeconomic characteristics of each zone, relative weights and averages associated with the entire system, respectively. The study aims to address the reliability needs of these households by analyzing and comparing the effectiveness of three key placement strategies.

A. Case 1: Baseline system reliability assessment without battery placement

This case established the base case reliability assessment for the 13-bus distribution system divided into three socioeconomic zones. Table III represents zonal and system-wide ENS values with mean ENS per zone to quantify the variability of the zone and system. Zone 1 exhibited the best stability and high reliability with a minimum ENS contribution that covered 16. 3% of the ENS throughout the system and a mean ENS per bus of 1.0204MWhr/year. With a low variability of 1.3641 MWhr, Zone 1 proved to have better infrastructure compared to other zones. In contrast, Zone 2 represented 45. 8% with an average ENS per bus of 3.4483MWhr/year. This was above system-wide average of 2.8957 MWhr/year, demonstrating Zone 2 as a low-income household. Overall, the system shows a variability of 5.7018 MWhr, reflecting inter-zone inconstancy, which was dominantly driven by Zones 2 and 3. The most striking contrast between the stability in Zone 1 and the vulnerabilities in Zones 2 and 3 points out the energy disparities within the system.

TABLE I
SOCIOECONOMIC CHARACTERISTICS OF COMMUNITY ZONES

Zone	Buses	AI$_z$ ($)	AE$_z$ (%)	AH$_z$ (%)
Zone 1	1,2,3,4,5,6	50,000	70	60
Zone 2	7,8,912,13	20,000	50	30
Zone 3	10,11	100,000	90	80

TABLE II
RELATIVE WEIGHTS AND SYSTEM-WIDE AVERAGES FOR DERIVING ω_z

Relative weights		System-wide averages	
ω_i	0.5	AI ($)	60,000
ω_e	0.3	AE (%)	70
ω_h	0.2	AH (%)	50

B. Case 2: Utility-centric battery placement, minimizing system-wide ENS without considering socioeconomic disparities

This analysis evaluated the system-wide and zonal impacts of three different battery placement scenarios. Batteries are placed on buses 5, 9, and 11 individually, and their effects on reliability are analyzed for each scenario. ENS values of various bus placements for both zonal and system are shown in Table IV. Table V shows the change in ENS compared to the baseline without battery (Case 1) and the corresponding percentage reduction across zones. The placement of the battery on bus 11 gives the largest system-wide ENS reduction of 46.45%. The placement on bus 9 follows with a 33.26% reduction, while the placement on bus 5 yields a minimal improvement of just 5.15%. As shown in Fig. 3, Zone 1 is seen to have low ENS, thus being inherently reliable due to proximity to generation sources. However, Zones 2 and 3 represent much higher values of ENS indicating that energy deficits are common in these zones under high demand. The placement on bus 11 achieves the most intense effect, as can be seen in Fig. 3 and Fig. 4. The utility-centric placement on bus 11 results in the maximum reduction in system-wide ENS. However, it focuses on the improvement in Zone 3, which is the high-income household, neglecting Zone 2, the low-income household. This shows the importance of community-aware approaches to address disparities across communities with different socioeconomic status.

C. Case 3: Community-aware battery placement, incorporating hardship weights

As shown in Fig. 5, the various socioeconomic status classifications highlight the disproportionate disparities in Zone 2, which makes it the prime candidate for targeted

TABLE III
ZONE-WISE ENS STATISTICS BEFORE STORAGE PLACEMENT

Zone	Total ENS (MWhr/year)	Mean ENS (MWhr/year)	Variability (MWhr)
Zone 1	6.1225	1.0204	1.3641
Zone 2	17.2416	3.4483	6.2898
Zone 3	14.2696	7.1348	6.7462
System	37.634	2.8957	5.7018

TABLE IV
ENS VALUES AFTER BATTERY PLACEMENT USING TRADITIONAL UTILITY-CENTRIC RELIABILITY METRIC FOR DECISION-MAKING

Zone	Placement	Zone 1 (MWhr)	Zone 2 (MWhr)	Zone 3 (MWhr)	System MWhr
Zone 1	Bus 5	4.1825	17.2416	14.2696	35.694
Zone 2	Bus 9	6.1225	9.6666	9.3261	25.115
Zone 3	Bus 11	6.1225	9.6666	4.3642	20.153

TABLE V
SYSTEM ENS IMPROVEMENT WITH BATTERY USING TRADITIONAL UTILITY-CENTRIC RELIABILITY METRIC

Placement	System ENS (MWhr)	% ENS Reduction
Battery at Bus 5	35.694	5.15%
Battery at Bus 9	25.115	33.26%
Battery at Bus 11	20.153	46.45%

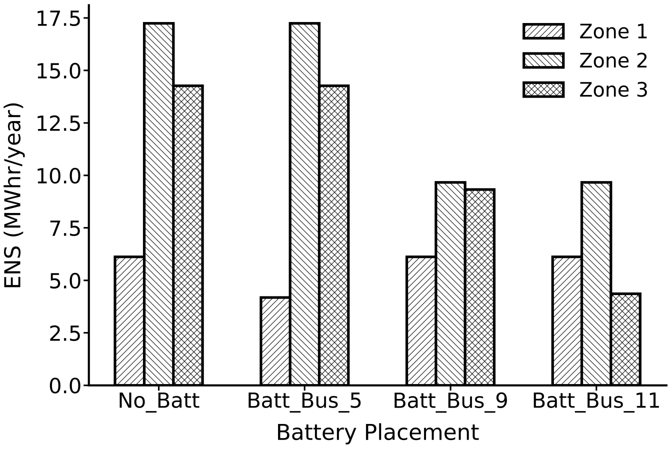

Fig. 3. Zonal ENS distribution for utility-centric battery placement

improvements. Table VII shows the various hardship-weighted ENS values for both zonal and system after battery placement. In Fig. 6, although the placement on bus 9 shows the same hardship-weighted ENS as on bus 11, ENS for Zone 3 further reduced which showed a disproportionate benefit against Zone 2. As Fig. 7, utility-centric battery placement on bus 11 provides the most system-wide reduction at 46.5%, benefiting Zone 3 with a 69.4% reduction, overlooking socioeconomic vulnerabilities of Zone 2,with a hardship index of 2.253. Under bus 11 placement, the hardship-weighted ENS of Zone 2 remains disproportionately high. In contrast, community-aware placement on bus 9 explicitly brings about a reduction of 43.9% in hardship-weighted ENS the low-income household which is Zone 2. Although marginally less, placement on bus 9, with 33% in the system-wide reduction, brings a balance between addressing community disparities and system performance. Battery placement at bus 9 proves to be the best way to bridge the gap between the system and socioeconomic considerations in reliability planning.

TABLE VI
HARDSHIP-WEIGHTED ENS VALUES AFTER BATTERY PLACEMENT USING COMMUNITY-AWARE RELIABILITY METRIC FOR DECISION-MAKING

Zone	Placement	Zone 1 (MWhr)	Zone 2 (MWhr)	Zone 3 (MWhr)	System MWhr
Zone 1	Bus 5	4.4627	38.8453	9.3893	52.697
Zone 2	Bus 9	6.5327	21.7788	6.1365	34.4481
Zone 3	Bus 11	6.5327	21.7788	2.8716	31.1832

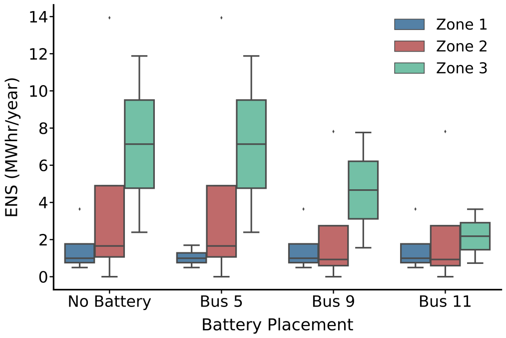

Fig. 4. A box plot showing zonal variability across battery placement for Utility-Centric battery placement.

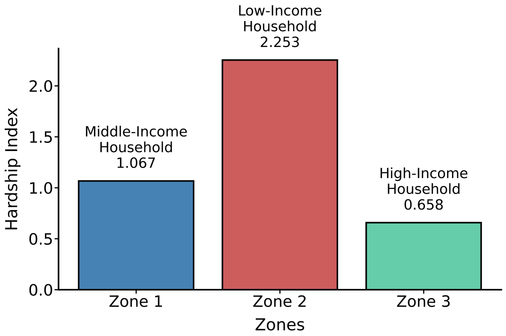

Fig. 5. Community hardship index and socioeconomic status across zones

V. CONCLUSION

To incorporate socioeconomic considerations and address the energy needs of low-income households in power grid reliability assessments and decision-making, this paper introduces a community-utility energy not supplied reliability metric. Three key socioeconomic factors—income, education, and homeownership—are identified to quantify community hardships resulting from power outages. The proposed community-utility ENS metric is applied within a battery storage placement framework. This approach enhances

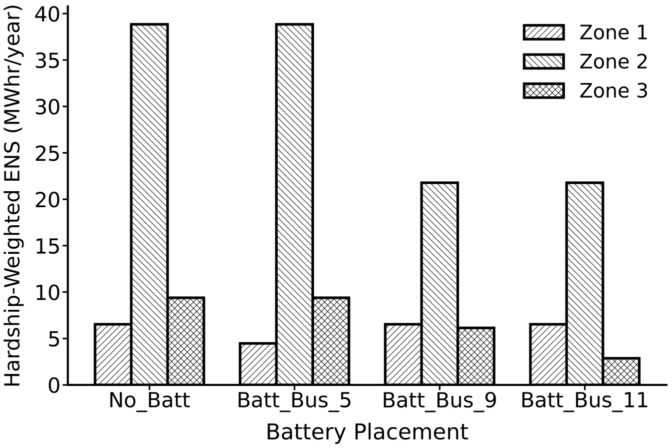

Fig. 6. Comparative ENS distributions across zones and battery placements, highlighting impact on vulnerable zones.

TABLE VII
MEAN ENS AND HARDSHIP-WEIGHTED MEAN ENS VALUES FOR EACH ZONE

Zone	**Mean ENS (No battery)**	**Mean ENS (With battery)**	**Hardship-Weighted Mean ENS (No battery)**	**Hardship-Weighted Mean ENS (with battery)**
Zone 1	1.0204	0.9126	1.0887	0.9737
Zone 2	3.4483	2.4383	7.7690	5.4934
Zone 3	7.1348	4.66	4.6946	3.0662

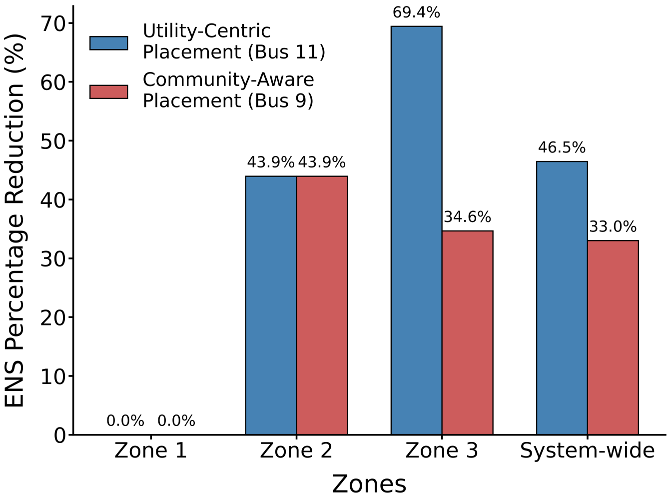

Fig. 7. Comparison of utility-centric and community-aware metrics for zonal and system-wide ENS percentage reductions.

reliability in low-income households while maintaining comparable overall system performance.

Three BESS placement strategies are compared on a 13-bus power distribution system. Results show the effectiveness of the proposed metric in achieving community-inclusive reliability planning that meets both technical and social objectives. This concept lays the foundation for a more community-aware and cost-effective energy system that ensures low-income households benefit from reliability improvements. Future work will scale the framework to larger and complex networks. Social factors such as family demographics and age distribution will be incorporated. Additionally, energy storage sizing and cost analysis will be explored together with advanced decision-making methods to further refine placement strategies, balancing performance, equity, and cost.

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