Energy Equity-Centered Planning of Community Microgrids

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Abstract

This paper examines the development of community microgrids (CMGs) as a strategy to address energy equity in under-served communities that have faced long-standing energy and environmental injustices. By introducing three novel equity-oriented indices-Community Energy Financial Index ($CEFI$), Community Energy Resiliency Index ($CERI$), and Community Energy Sustainability Index ($CESI$)—we provide a framework to evaluate and address energy-related inequalities. The framework quantifies how deploying CMGs can systematically improve access to clean and reliable energy. A two-stage stochastic mixed-integer programming model, utilizing Benders decomposition, is proposed to optimize CMG planning and operation under operational uncertainties. A case study of three energy-poverty neighborhoods in the Greater Houston area reveals significant improvements in energy equity metrics, such as affordability, cost-effectiveness, resilience, and sustainability, through targeted investment and strategic CMG planning. Our analysis demonstrates that, under various budget scenarios and technology selections, equity-focused CMGs consistently outperform the business-as-usual case and conventional approaches prioritizing cost minimization. These findings underscore the potential of CMGs to foster equitable, resilient, and sustainable energy systems for the future.

Keywords:

Community Microgrid, Energy Equity, Energy Justice, Microgrid Planning, Benders Decomposition

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Nomenclature

Indices

ω	Indices for scenarios
ch	Superscript for energy storage charging mode
dch	Superscript for energy storage discharging mode
i	Index for DERs
t	Subscript for time step

Parameters

η	energy storage efficiency
ν	value of lost load
ρ	Market price for electricity
B	Budget
c	generation price for dispatchable units
C^{max}	rated capacity of energy storage systems
CC	annualized investment cost of generating units
CE	annualized investment cost of storage - power
COL	cost of load shedding
CP	annualized investment cost of storage - energy
D	load demand
D^{max}	annual peak load
EM	emission production
K	large positive constant
k	coefficient of present-worth value
P^{max}	max output power of DERs
P_M^{max}	flow limit between microgrid and the main grid
Pr_M^{out}	probability of main grid power outage
λ	objective function weights
ψ	proportion of load shedding allowed

Sets

S	Set of energy storage devices
T	Set of time indices
W	Set of non-dispatchable generators
Ω	Set of scenarios
G	Set of dispatchable generators

Variables

P_M^+	power bought from main grid
P_M^-	power sold to main grid
P	DER output power
LS	Load Shedding
x	DER investment state

1. Introduction

In an era of relentless pursuit for sustainable solutions, microgrids have emerged as a transformative force in redefining energy generation, distribution, and consumption in our modern energy landscape. Conventional centralized power grids, while effective, are vulnerable to extreme weather events, cyberattacks, and aging infrastructure. In contrast, microgrids offer a decentralized and resilient approach to energy generation and distribution. By enabling communities to generate and manage their electricity locally, microgrids enhance energy security, reduce transmission losses, and promote adaptability in the face of disruptions. Furthermore, they facilitate the incorporation of sustainable energy sources, a crucial step in addressing climate change. The adaptability and versatility of microgrids make them not only a feasible option but an essential building block for a sustainable future. However, the importance of microgrids could extend beyond technological innovation: due to their localized nature, microgrids can be the key to addressing some of society's most pressing challenges, especially when thoughtfully integrated into the communities they are serving.

Equity, a fundamental principle of social justice, has become a guiding criterion for designing and implementing energy solutions. The concept of equity encompasses financial, resiliency, and environmental dimensions, ensuring fair and inclusive access to benefits. As the world strives for sustainable energy solutions, it is imperative to guarantee that these advantages are distributed equitably, preventing disproportionate favoring of wealthier regions and avoiding the neglect of marginalized communities. Under this context, understanding the convergence of microgrids and equity is crucial. Addressing equity concerns involves rectifying historical disparities in access to resources and opportunities, thereby ensuring that all communities can partake in and benefit from sustainable energy advancements. This involves creating policies and frameworks that specifically target under-served areas, making technology and resources accessible to those who need them most. By doing so, we can build more resilient, fair, and environmentally friendly energy systems that serve the needs of every community, fostering a more just and sustainable future.

Microgrids, as catalysts for equity, can offer many key benefits in the realm of equity. For instance, they enable energy cost reduction and income generation through the integration of local renewable energy sources. This alleviates financial burdens on residents and catalyzes economic development within communities. Additionally, microgrids enhance the resilience of local energy systems, especially in the face of climate-related disasters, ensuring the continuity of vital services during crises, protecting vulnerable populations, and reducing disparities in disaster response. By using clean energy sources and greenhouse gas emissions reduction, microgrids actively contribute to environmental equity, safeguarding the health and well-being of residents in marginalized communities, who often bear a disproportionate burden of environmental pollution.

Despite the strong connections between microgrids and community-oriented energy equity, challenges remain in formulating a systematic framework that effectively captures equity-related concerns and considerations during the planning process of community microgrids. While numerous studies have highlighted the successful development and implementation of community microgrid projects worldwide [1], the full benefits and potentials of these systems have not been comprehensively explored. For instance, how to accurately identify and prioritize the needs of marginalized communities through understanding the unique energy demands, financial constraints, and environmental vulnerabilities of these communities? What is the most effective strategy to plan and manage the equitable implementation of community microgrids? How to evaluate the success of a community microgrid: it is evident that we need to evaluate not only the technical and economic performance but also the social and environmental benefits to promote widespread adoption.

Realizing these critical gaps in the literature, in this paper, we focus on developing a comprehensive framework that systematically addresses equity-related concerns in the planning and implementation of community microgrids. We aim to provide an engineering-oriented methodology for identifying and prioritizing the needs of marginalized communities, considering their unique energy demands, financial constraints, and environmental vulnerabilities. Additionally, we investigate effective strategies for managing the equitable implementation of community microgrids and propose metrics for evaluating their success, encompassing technical performance, economic viability, and social and environmental benefits.

This study aims to answer the following question: How can community microgrids be planned in a way that improves energy equity in under-served neighborhoods, with a focus on financial accessibility, resiliency, and sustainability? To address this research question we plan to (1) introduce novel community-level equity indices to evaluate financial, sustainability, and resiliency dimensions of energy access, (2) develop a two-stage stochastic mixed-integer programming model to guide equitable community microgrid planning under uncertainty, and (3) apply this framework to real-world low-income communities in Houston to demonstrate how equity-centered planning outperforms traditional cost-minimization approaches.

Simulation results show that microgrids can simultaneously enhance financial stability, resiliency, and environmental sustainability while ensuring equitable energy distribution. Compared with no microgrid benchmark, the proposed equity-centered planning approach results in 78% improvement in Community Energy Financial Index ($CEFI$), 227% improvement in Community Energy Sustainability Index ($CESI$), and 24% improvement in Community Energy Resiliency Index ($CERI$). These results demonstrate how community microgrids can contribute to a more just and resilient energy landscape.

2. Literature Survey

2.1. Microgrids and their community deployment

Community microgrids are localized energy networks that integrate distributed renewable resources, storage, and controllable loads, and can operate independently or grid-connected, enhancing resilience and flexibility [2, 3, 4]. When embedded in communities, microgrids deliver economic, environmental, and social benefits—offering more affordable power, supporting energy security, and fostering sustainable local development [5, 6]. They can help alleviate energy insecurity, defined as the inability to meet basic household energy needs [7], and reduce environmental footprints by integrating renewable sources and cutting emissions [8, 9, 10, 11, 12]. However, implementing community microgrids involves more than just technical optimization; it also requires addressing policy, regulatory, and economic barriers, ensuring equitable access, and involving local stakeholders to balance social interests, affordability, and long-term sustainability [6, 1].

Recent literature highlights a gap in addressing energy justice in community microgrid planning and operation. While technical optimization has been well-explored, socio-economic impacts on residents remain underexamined. For instance, some studies show significant socioeconomic disparities in adopting clean energy technologies like rooftop solar, highlighting the need for energy justice to ensure equitable access to renewable energy resources across diverse communities [13]. Additionally, research on energy rationing preferences during blackouts shows that while residents support a market-based system where consumers could pay more for higher energy quotas, this approach may disproportionately benefit wealthier households and leave economically weaker consumers without power [14]. These findings underscore the need to integrate energy justice principles into community microgrids, ensuring equitable access to clean energy, especially during crises.

2.2. Community microgrid deployment: Optimization Challenges and Solutions

Community microgrids face complex optimization challenges due to uncertainties, scalability, technical skill gaps, and system complexity [15, 16]. Common optimization objectives include minimizing costs, balancing supply and demand, reducing GHG emissions, and coordinating distributed resources. Approaches span exact methods, heuristic/meta-heuristic techniques, and model predictive control (MPC).

Exact mathematical models often rely on bilevel formulations and stochastic programming to allocate resources, manage battery storage, and facilitate local energy markets [17, 18, 19, 20, 21, 22, 23]. These methods provide precise solutions but often assume simplified problem structures or overlook factors like battery degradation.

Transactive Energy (TE) frameworks incorporate flexible demand and prosumer behaviors into optimization, enabling price-based coordination and peer-to-peer trading [24, 25, 26, 27, 28]. These TE approaches, employing distributed control and market mechanisms, can reduce central coordination burdens and enhance scalability.

Meta-heuristic methods (e.g., PSO, DE, genetic algorithms) relax modeling assumptions to handle nonlinearities and uncertainties, particularly in load and price forecasts [16, 29, 30, 31, 32]. Although these methods can explore large, complex solution spaces, they may demand high computational resources and struggle with dynamic operations at scale.

Overall, community microgrid optimization increasingly integrates diverse approaches—exact, transactive, and meta-heuristic—to address technical, economic, and regulatory complexities, seeking robust and adaptive solutions that account for real-world uncertainties and evolving community needs.

2.3. Equity and Equity Metrics

To ensure that the advantages of grid modernization and the adoption of clean energy reach all individuals, it has become a consensus that developing energy equity metrics and a quantifiable evaluation framework will be imperative for assessing energy equity and corresponding data analysis techniques.

Table 2: Definitions of energy inequities

Energy Inequity	**Definition**
Energy poverty	The lack of access to basic, life-sustaining energy.
Energy burden	The percent of a household's income spent to cover energy cost.
Energy insecurity	The inability of a household to meet their basic energy needs.
Energy vulnerability	The propensity of a household to suffer from a lack of adequate energy services in the home.

Energy justice is conceptualized as integrating justice principles, fairness, and social equity into energy systems and energy systems transitions. The concept of energy justice, also known as energy equity, has emerged as a guiding principle aimed at rectifying disparities exacerbated by energy systems [33]. These disparities encompass various aspects of the energy system, including energy poverty, energy burden, energy insecurity, and energy vulnerability, among others (as detailed in Table 2). Advancing energy equity necessitates a comprehensive comprehension of how the energy system intersects with and influences various factors encompassing the environment, economy, public health, security, and resilience. Crucially, these intersections must be linked with demographic variables such as income, race, gender, ethnicity, employment, location, ability status, homeownership, and educational attainment [34]. The process of dissecting and discerning the impacts across these demographic indicators allows for the identification of individuals within society who are vulnerable, significantly affected, under-served, or marginalized due to the energy system [35].

One might consider the concept of equity and categorize it in different ways. The most established method of categorization in the literature is into either equity paradigms or equity metrics.

In the former case, equity paradigms are typically divided into four groups: Recognition, Distributive, Restorative, and Procedural. In the latter case, the metrics defined to evaluate and quantify equity in communities are categorized into three groups: target population identification, investment decision-making, and program impact assessment. We will discuss them in detail in sections 2.3.1 and 2.3.2.

2.3.1. Equity Paradigms

In examining the multifaceted dimensions of equity within the realm of social studies and energy, literature provides a comprehensive framework categorizing equity paradigms into four distinct categories: Recognition, Distributive, Restorative, and Procedural justice. Tarekegne et al. [36] utilize an energy justice conceptual framework to underscore the importance of integrating these dimensions for equitable decision-making in energy transitions. This approach ensures that varying vulnerabilities and needs across community groups are acknowledged (Recognition), injustices and their distribution are identified (Distributive), stakeholders are inclusively engaged in decision-making processes (Procedural), and measures are taken to mitigate past injustices in the shift from traditional to modernized energy systems (Restorative). Energy Equity Project by School for Environment and Sustainability [37] further elaborates on these paradigms, highlighting the critical role of recognizing distinct vulnerabilities (Recognition), ensuring diverse representation in decision-making (Procedural), addressing the equitable distribution of benefits and harms (Distributive), and fostering opportunities to repair harm and address needs post-injustice (Restorative). These insights are echoed in the OŃeil et al. [38], which delves into the unequal allocation of benefits and burdens (Distributive), the practice of cultural domination and misrecognition (Recognition), the fairness of decision-making processes (Procedural), and responses to those impacted by the burdens of energy projects (Restorative). Collectively, these sources provide a robust framework for understanding and implementing equity in energy transitions, especially within under-served communities.

Also, OŃeil et al. [38] presents table 3, which categorizes some general metric concepts under each equity umbrella paradigm, highlighting the multidimensional approach to addressing equity within the energy sector. This categorization underscores the complexity of achieving energy equity, dividing the effort across procedural and recognition equity (emphasizing due process and accountability), distributive equity (focusing on affordability and availability), and restorative equity (centering on intra- and inter-generational sustainability and responsibility). Such a framework is pivotal in understanding where new metrics might align and how they contribute to broader equity objectives.

2.3.2. Equity Metrics

Recent policy initiatives have emphasized the importance of developing clear metrics to gauge progress toward achieving energy equity and justice. Energy equity seeks to mitigate disparities in the distribution of benefits and burdens by examining how the energy system's historical and current conditions have favored or disadvantaged different segments of the population. The core insight across recent studies is that energy equity is not inherently achieved through market-driven adoption alone but requires intentional policy interventions informed by robust equity metrics to address disparities. Whether through electricity pricing [39], renewable energy programs [13], or urban planning [40], equity concerns arise when access to energy benefits is unevenly distributed across different socioeconomic and geographic groups. These studies highlight that without effective equity metrics—such as disparity indices, spatial analysis, and predictive models—disparities may persist or even worsen over time, even when equity is a stated goal.

In this context, a comprehensive framework, as outlined in key reports, categorizes these metrics into three types: target population identification, investment decision-making, and program impact assessment [41]. Table 4 shows these categories and some of the important metrics within each of them.

Target population identification metrics offer descriptive analytics about populations eligible for support programs and measure the distribution of benefits and burdens. Some of these metrics include Program equity index, Program accessibility, Energy cost index, Energy burden index, Late payment index, Appliance performance, and Household human development index. Collectively, these metrics help identify the populations most in need of support, ensuring that benefits are fairly distributed.

Investment decision-making metrics evaluate the potential impacts of investments on equitable

Table 3: Equity metrics and Paradigms [38]

Procedural and Recognition (due process and accountability)	**Distributive (affordability and availability)**	**Restorative (intra-and inter-generational sustainability and responsibility)**
- Representativeness and inclusiveness of planning processes for all affected stakeholders. - Responsiveness of planning processes to public participation and fairness of decisions. - Transparency of planning processes and decisions.	- Electricity cost burden (i.e., household electricity bills/income). - Electricity affordability gap. - Electricity quality (e.g., geographic disaggregation of outage frequency/severity; restoration efficiency). - Electricity programs (e.g., tax credits; energy efficiency) and technology (e.g., BTM solar and storage) accessibility and performance (e.g., participation/investment demographics; distribution of savings/costs, reliability/resilience, or other benefits/burdens). - Social burden (i.e., effort and ability to access critical services).	- Economic (e.g., job training/job quality; energy resource ownership/governance; reparation of electricity cost burden shouldered by energy burdened communities). - Environmental (e.g., natural resource replenishment; generation/storage resource siting). - Social (e.g., improvements in household-human development index; establishment of safeguard/grievance redress mechanisms).

Table 4: Overview of Equity Metrics

Community Descriptive Metrics	**Investment Distribution Metrics**	**Program Results Metrics**
Program equity index	Community Acceptance Rating	Program Acceptance Rate
Program accessibility	Program Funding Impact	Energy savings
Energy cost index	Energy Use Impacts	Energy cost savings
Energy burden index	Energy quality	Energy Burden Change
Late payment index	Workforce Impact	Change in HDI Score
Appliance performance		
Household human development index		

outcomes by comparing different populations. Notable metrics include Community acceptance rating, Program funding impact, Energy use impacts, and Workforce impact. These metrics are crucial for assessing how investments can advance equitable outcomes and identify areas needing attention.

Finally, program impact assessment metrics track the effectiveness of support programs in assisting target communities. These include Program acceptance rate, Energy savings, Energy cost savings, Change in energy burden, and Changes in the Human Development Index (HDI). These metrics are vital for evaluating the impact of energy programs and for planning future initiatives to enhance energy equity.

Together, these metrics form a robust framework that enables stakeholders to measure and track progress toward energy equity and justice, supporting informed decision-making and promoting inclusivity in energy resource distribution.

Table 5 Shows how different equity metrics aligns with equity paradigm categories and equity metric categories.

Compared with the literature, contributions of this paper can be summarized as:

- We introduce three new community-based equity metrics designed to assess the financial, resilience, and environmental impact of community microgrids. These metrics offer a novel approach to quantitatively evaluate how well communities are managing these crucial areas.

Table 5: Summary of Equity Metrics Categories versus Equity Paradigms

	Procedural and Recognition	**Distributive**	**Restorative**
Community Descriptive Metrics	Household-Human Development Index	Appliance performance, Program accessibility, Program equity index, Energy cost index, Energy burden index, Late payment index	
Investment Distribution Metrics	Workforce Impact, Community Acceptance Rating	Program Funding Impact, Energy quality	Energy Use Impacts
Program Results Metrics	Program Acceptance Rate		Energy savings, Energy cost savings, Energy Burden Change, Change in HDI Score

- We formulated the problem as a two-stage stochastic mixed-integer programming model and then reformulated it utilizing Benders decomposition to efficiently solve it. This approach allowed us to address both investment planning and operational planning in a sequential manner, optimizing the deployment of community microgrids to enhance financial stability, resiliency, and environmental sustainability in under-served communities.
- We provide investment insights for microgrid infrastructures, including dispatchable energy resources (DER) generators, solar panels, and batteries, specifically tailored for scenarios with limited budgets. This guidance is crucial for policymakers and investors aiming to optimize the deployment of renewable energy technologies in a cost-effective manner.

These contributions aim to bridge gaps in current research and offer practical solutions that can be applied to enhance sustainability and equity in community energy systems.

The rest of the paper is organized as following. In section 3 we define our equity metrics. Then in section 4 we will formulate the mathematical model of deploying a microgrid in community. In section 5 we discuss about the case study and numerical results. Finally in section 6 we conclude the paper.

3. Problem Definition

3.1. Target Community Index

In this paper, we introduce three new equity indices tailored specifically for communities: the Community Financial Index ($CEFI$), the Community Sustainability Index ($CESI$), and the Community Resiliency Index ($CERI$). These indices were chosen to reflect the three most measurable and urgent aspects of energy equity in under-served communities: affordability ($CEFI$), reliability during disruptions ($CERI$), and environmental sustainability ($CESI$). They align with the widely recognized equity paradigms of distributive and restorative justice, and they were informed by established energy system concepts such as energy burden, loss of load probability, and greenhouse gas intensity. Specifically, $CEFI$ and $CERI$ reflect distributive equity by focusing on affordability and availability, while $CESI$ represents restorative equity by addressing long-term environmental responsibility and sustainability. Together, these indices form a balanced and practical framework to evaluate the real-world impact of community microgrids in a quantifiable way.

We recognize that microgrids have emerged as transformative solutions, and they have the potential to significantly enhance financial stability, environmental sustainability, and overall resilience in communities. Through the development of these equity indices, we aim to shed light on the pivotal role that microgrids play in reshaping the landscape of community well-being. Our objective is to underscore the importance of these equity measures as we strive to enhance and optimize the financial, sustainability, and resiliency aspects of communities, ultimately paving the way for a more equitable, sustainable, and resilient future. By quantifying the impact of microgrids on these critical dimensions, we provide a framework for communities to make informed decisions and drive positive change in their pursuit of equity and sustainability.

3.1.1. Community Financial Index

The equation provided in 1 calculates the $CEFI$, a critical metric used to gauge the financial health and stability of a community. In formulating this index, we drew on the concept of *Affordability* or *Energy Burden*—commonly defined as the ratio of a household's energy costs to its income—by comparing total net energy expenditures against a normalizing threshold. However, rather than focusing on a single household's energy bill relative to income, we adapted the idea for a community microgrid context by (i) aggregating costs for both local generation and grid purchases, (ii) subtracting revenues from grid sales, and (iii) comparing the resulting net cost to an upper limit R that captures the maximum feasible expense for the community. This normalization ensures that $CEFI$ remains between 0 and 1, aligning well with equity-focused studies while also reflecting the operational realities of shared microgrid infrastructures. Each component of the equation thus contributes to the index by revealing a different dimension of the community's financial situation, ultimately providing a holistic measure of microgrid affordability.

$$CEFI = CEFI^{max} - \frac{(\sum_{i \in G, t \in T} P_{it} c_{it} + \sum_{t \in T} P^{+}_{M,t} \rho (1 - Pr^{out}_{M,t}) - P^{-}_{M,t} \rho)}{R} \tag{1}$$

$CEFI$, short for the Community Financial Index, represents the community's overall financial well-being, with a higher value indicating better financial health. $CEFI^{max}$ serves as a benchmark for assessing how close the actual $CEFI$ is to its maximum potential. The equation involves summations over time periods and variables, where c_{it} signifies power generation costs for generator i at time t, and P_{it} represents the generated power amount. These terms collectively sum up power generation costs, reflecting an aspect of the community's financial situation. Additionally, the equation incorporates financial transactions with the main grid over time, accounting for both expenses (buying power) and income (selling excess power), with R acting as a constraint and denominator to scale the $CEFI$. In essence, this equation provides a holistic evaluation of a community's financial health, encompassing various financial factors to quantify its overall stability and guide financial decision-making. Also, $P^{+}_{M,t}\rho$ stands for the cost incurred by the community when purchasing electricity from the main grid during a specific time period t, reflecting the expense of obtaining power externally. The symbol ρ serves as a coefficient within the equation, determining the market price of electricity. Moreover, $Pr^{out}_{M,t}$ accounts for the probability of power unavailability from the main grid, considering the likelihood of grid outages during a given time period, with a lower value indicating a higher probability of uninterrupted power supply. Lastly, $P^{-}_{M,t}\rho$ signifies the income generated by the community when selling excess electricity back to the main grid during a specific time t capturing the financial benefits obtained from exporting surplus power to the grid.

In summary, this equation allows for a comprehensive evaluation of a community's financial health by considering multiple financial factors. It accounts for the cost of power generation from various sources, financial transactions with the main grid, and constraints on power generation costs. The resulting $CEFI$ provides a single numerical value that quantifies the community's overall financial stability and well-being, aiding in financial planning and decision-making.

3.1.2. Community (Energy) Resilience Index

The equation presented in (2) calculates the $CERI$, a crucial metric used to assess the resilience of a community in the face of disruptions, particularly in its power supply. In deriving this index, we took inspiration from well-known reliability and resilience metrics. Specifically, the first term is inspired by the *Loss of Load Probability* concept, capturing the risk of relying on the main grid when it may be unavailable. The second and third terms, related respectively to battery state of charge and local renewable generation, reflect ideas from *Expected Energy Not Served* and *System Average Interruption Duration Index*—in other words, when batteries are kept sufficiently charged and renewable resources are maximized, the expected amount of unserved energy is reduced, thus shortening potential interruptions. By weaving these established principles into a single framework, weighted and normalized to stay between 0 and 1, the resulting $CERI$ offers a holistic view of community microgrid resilience.

$$CERI = CERI^{max} - (\gamma_1 \frac{\sum_{t \in T} P^{+}_{M,t} Pr^{out}_{M,t}}{O^{max}} + \gamma_2 (1 - \frac{\sum_{t \in T, i \in S} SOC_{t,i}}{Cap^{max}}) + \gamma_3 (1 - \frac{\sum_{t \in T, i \in W} P_{t,i}}{P^{max}})) \quad (2)$$

$CERI$ equation comprises several essential components. To begin, $CERI$ stands for the Community Resiliency Index, which is a numerical value quantifying a community's level of resilience, with a higher $CERI$ signifying greater resilience. $CERI^{max}$ represents the maximum potential value that the $CERI$ can attain, serving as a benchmark to assess how close the actual $CERI$ is to its peak. Within the equation, there's a summation over time periods includes $\sum_{t \in T} P^{+}_{M,t} Pr^{out}_{M,t}$, where $P^{+}_{M,t}$ represents power demand from the main grid at each time t indicating community reliance, and $Pr^{out}_{M,t}$ captures the probability of main grid power outages at each t. This multiplication, summed over time, quantifies the total impact of these outages. Lastly, D^{max} in the denominator acts as a constraint, scaling the $CERI$ by dividing the sum of load shedding and outage impact. Further, there is another summation $\sum_{t\in T,i\in S} SOC_{t,i}$ over time and storage units S of the state of charge ($SOC_{t,i}$), representing the capability of the storage units to handle sudden impacts from external disruptions. The fraction $1 - \frac{\sum_{t\in T,i\in S} SOC_{t,i}}{SOC^{max}}$ captures the proportion of the maximum state of charge, indicating the resilience capacity of the storage units. In the last part, $\sum_{t\in T,i\in W} P_{t,i}$ is the summation over time and renewable energy sources W of the available renewable power, $P_{t,i}$. This component reflects the community's ability to cope with power cuts using renewable energy. The fraction $1 - \frac{\sum_{t\in T,i\in W} P_{t,i}}{P^{max}}$ normalizes the available renewable power between 0 and 1, indicating the resilience capacity concerning renewable energy sources.

In summary, this equation provides a holistic assessment of a community's resilience regarding its power supply, considering load shedding, main grid reliance, and outage probabilities, yielding a single numerical $CERI$ value that aids decision-makers in enhancing the community's ability to withstand power disruptions and other challenges.

3.1.3. Community Sustainability Index

The equation provided in (3) calculates the $CESI$, a metric used to assess the environmental impact of a community's energy generation and consumption. In formulating this index, we drew upon the concept of *GHG intensity*, which typically measures total greenhouse gas emissions relative to the quantity of electricity produced or consumed. We tailored this idea to the community microgrid level by separately accounting for local generation emissions ($EM_i P_{it}$) and main-grid emissions ($EM_M P^+_{M,t}(1 - Pr^{out}_{M,t})$) before normalizing by an upper bound EM^{max}. Through this approach, the resulting $CESI$ remains between 0 and 1, offering a concise snapshot of the microgrid's environmental footprint and how effectively it minimizes total emissions relative to a maximum threshold. Each term thus captures a distinct dimension of the community's sustainability performance.

$$CESI = CESI^{max} - \frac{\sum_{i\in G,t\in T} EM_i P_{it} + \sum_{t\in T} EM_M P^+_{M,t}(1 - Pr^{out}_{M,t})}{EM^{max}} \tag{3}$$

Higher $CESI$ typically indicating a lower environmental impact, signifying a more eco-friendly community. $CESI^{max}$ represents the maximum potential value the $CESI$ can reach, serving as a benchmark for assessing the proximity of the actual $CESI$ to its peak. Within the equation, there's a summation over two variables, i and t, denoted as $\sum_{i,t} EM_{i,t}P_{it}$. Here, i represents various dispatchable power generators in the community, t denotes different time periods, $EM_{i,t}$ signifies the environmental impact or pollution from generator i at time t quantifying emissions from each generator, and P_{it} represents the power generation from generator i at time t, summing up the environmental impact of dispatchable generators over time. Further, another summation over time is indicated by $\sum_t EM_M P^+_{M,t}(1 - Pr^{out}_{M,t})$, representing the environmental impact or pollution associated with purchasing power from the main grid at each time t. This component considers EM_M as the environmental impact of buying power from the main grid, $P^+_{M,t}$ as the power demand from the main grid at each time t and $(1 - Pr^{out}_{M,t})$ accounting for the probability of grid power availability while considering outages. This term quantifies the environmental impact of the community's reliance on the main grid, considering potential power disruptions. Lastly, EM^{max} in the denominator serves as a scaling factor, dividing the sum of emissions from dispatchable generators and the environmental impact of power purchases from the main grid by EM^{max}. This scaling helps maintain $CESI$ within a manageable range and represents the maximum allowable pollution level within a specified time horizon, acting as an environmental constraint. In summary, this equation provides a comprehensive assessment of a community's environmental performance concerning energy generation and consumption. It accounts for emissions from dispatchable generators, the environmental impact of buying grid power, and sets a pollution limit. The resulting $CESI$ yields a single numerical value, facilitating the evaluation and enhancement of the community's environmental sustainability while reducing pollution over time.

4. Mathematical Model

To achieve optimal decision-making in the context of implementing a microgrid within a community, we propose an optimization framework that encompasses two key phases: "Investment Planning" and "Operation Planning" (refer to Algorithm 1). Our strategy involves addressing these two stages sequentially. The Investment Planning phase, conducted in the initial stage, is framed as an integer programming model, while the Operation Planning subproblem, handled in the subsequent stage, is formulated as a linear programming model.

Algorithm 1 Benders Decomposition Algorithm for Microgrid Optimization

Data: Decision variables X_{ig}, X_{iw}, X_{is}
Result: Optimal mix of DER installation and operation plan
Initialization:
  Set iteration counter $k = 0$
  Initialize the binary variables x_i for all $i \in \{S, W, G\}$
  Set the upper bound $UB = \infty$ and lower bound $LB = -\infty$.
while $|UB - LB| \geq \epsilon$ **do**
  Solve the master problem by maximizing $E_\omega[Q_\omega(x_i)]$ to get optimal x_i^k.
  Fix $x_i = x_i^k$.
  Solve the subproblem by maximizing $Q_\omega(\overline{x}_i)$
  if *the subproblem is feasible* **then**
    Generate an optimality cut and add it to the master problem
  else
    Generate a feasibility cut and add it to the master problem.
  end
  Update the lower bound LB and upper bound UB:
    $LB = max(LB, \text{Objective value of Master Problem})$
    $UB = min(UB, \text{Objective value of Subproblem})$
  Set $k = k + 1$
end

In the Investment Planning phase, we aim to ascertain the optimal configuration of distributed energy resources. This includes dispatchable, nondispatchable, and storage units. Our objective is to maximize the expected value of a parameter denoted as $Q_\omega(x)$ across various scenarios $\omega \in \Omega$ as shown in 4. $Q_\omega(x)$ is intricately tied to the subproblem's objective function and is refined iteratively through the introduction of optimality and feasibility cuts, improving the master problem's solution.

Several constraints play a pivotal role in this phase. Constraint 5 ensures that the installed DERs' collective capacity meets the annual peak load. This is fundamental for ensuring the microgrid's self-sufficiency and its continuous functionality as an essential community asset. Constraint 6 specifies that the variables related to the DERs' installation status are binary, signifying their on/off state. Moving on to the Operation Planning phase in the second stage, our primary aim is to maximize what we refer to as the "Community Energy Index" (CEI). This index is a composite measure that combines Three sub-indices detailed in Section 3.1 of our paper. Notably, the assignment of weight parameters to each sub-index, a crucial aspect of CEI calculation, is not explicitly addressed in this paper. The objective under consideration includes the $CEFI$, $CERI$, and $CESI$ (as stated in equation 7).

$$\max_{x_i} E_\omega[Q_\omega(x_i)] \tag{4}$$

$$D_t \leq \sum_{i \in G,W,S} P_i^{max} x_i, \qquad \forall t \tag{5}$$

$$x_i \in \{0,1\}, \qquad \forall i \in G,W,S \tag{6}$$

In Goal Programming, objectives follow a hierarchy, where the highest-priority goal takes precedence. When there is a predefined dominance order among the goals, a sequential algorithm (refer to Figure 2) is implemented to optimize them. For instance, if there are N goals following a dominance order, with goal n being prioritized before goal m (where $n < m$), a sequential optimization approach is employed.

In our context, where the maximum achievable value for each index (i.e., goal) is known to be 1, we find Lexicographic Goal Programming to be a fitting approach for our problem.

To formalize the objective function for CMPI, given a set of parameters denoted as x_i (representing the outputs of the first stage), and considering each scenario, we utilize equation 7:

$$Q_\omega(\overline{x}_i) = \max_{P,LS} E_\omega[\lambda_1 CEFI_\omega + \lambda_2 CERI_\omega + \lambda_3 CESI_\omega] \tag{7}$$

Moreover, we introduce a budget constraint 8 to ensure that the total investment and operation costs do not exceed the available financial resources. The investment cost for generating units (both dispatchable and nondispatchable) is determined by their generating capacity. In contrast, the investment cost for energy storage systems hinges on their rated power and energy storage capacity. The total operation cost comprises several components, including:

Generation cost of dispatchable units. The cost associated with purchasing energy from the main grid. Revenue generated from selling excess power to the main grid. Costs incurred due to unserved energy. It is important to note that, given their renewable nature, we assume zero generation costs for nondispatchable units and energy storage systems. The total cost is calculated as the present-worth value, factoring in the discount rate. This rate reflects the interest rate used to determine the present value and accounts for the temporal value of money.

In summary, our proposed approach for implementing a community microgrid seeks to maximize the Community Microgrid Performance Index (CMPI) through a two-stage optimization process, integrating Investment Planning and Operation Planning, while adhering to budgetary constraints and considering multiple socio-economic and environmental objectives.

$$\sum_t \Bigg(\sum_{i \in W} k_t CC_{it} P_i^{max} \hat{x}_i + \sum_{i \in S} k_t (CP_{it} P_i^{max} + CE_{it} C_i^{max}) \hat{x}_i + \sum_{i \in G} k_t c_i P_{it\omega} + k_t \rho_t (P_{M,tw}^+ - P_{M,tw}^-) + k_t v_t LS_{t\omega} \Bigg) \leq B \qquad \forall \omega \in \Omega \tag{8}$$

$$\sum_{i \in W,G} P_{it\omega} + \sum_{i \in S} (P_{it\omega}^{dch} - P_{it\omega}^{ch}) + P_{M,t\omega}^+ - P_{M,t\omega}^- + LS_{t\omega} = D_t, \qquad \forall t \in T, \forall \omega \in \Omega \tag{9}$$

$$P_{M,t\omega}^+ \leq P_M^{max}, \qquad \forall t \in T, \forall \omega \in \Omega \tag{10}$$

$$P_{M,t\omega}^- \leq P_M^{max}, \qquad \forall t \in T, \forall \omega \in \Omega \tag{11}$$

$$P_{it\omega} \leq P_i^{max} \hat{x}_i, \qquad \forall t \in T, \forall i \in G, \forall \omega \in \Omega \tag{12}$$

$$P_{it\omega} = P_i^{max} \hat{x}_i, \qquad \forall t \in T, \forall i \in W, \forall \omega \in \Omega \tag{13}$$

$$P_{it\omega}^{ch} \leq P_i^{ch,max} \hat{x}_i, \qquad \forall t \in T, \forall i \in S, \forall \omega \in \Omega \tag{14}$$

$$P_{it\omega}^{dch} \leq P_i^{dch,max} \hat{x}_i, \qquad \forall t \in T, \forall i \in S, \forall \omega \in \Omega \tag{15}$$

$$0 \leq \sum_{k \leq t} (P_{ik\omega}^{ch} - \frac{P_{ik\omega}^{dch}}{\eta_i}), \qquad \forall t \in T, \forall i \in S, \forall \omega \in \Omega \tag{16}$$

$$\sum_{k \leq t} (P_{ik\omega}^{ch} - \frac{P_{ik\omega}^{dch}}{\eta_i}) \leq C_i^{max} \hat{x}_i, \qquad \forall t \in T, \forall i \in S, \forall \omega \in \Omega \tag{17}$$

$$\hat{x}_i \leq K \sum_t P_{it\omega}, \qquad \forall i \in G, W, \forall \omega \in \Omega \tag{18}$$

$$\hat{x}_i \leq K \sum_t P_{it\omega}^{ch}, \qquad \forall i \in S, \forall \omega \in \Omega \tag{19}$$

$$\hat{x}_i \leq K \sum_t P^{dch}_{it\omega}, \qquad \forall i \in S, \forall \omega \in \Omega \tag{20}$$

$$LS_{t\omega} \leq \psi D_t, \qquad \forall t \in T, \forall \omega \in \Omega \tag{21}$$

$$\sum_{i \in W,G} P_{it\omega} + \sum_{i \in S} (P^{dch}_{it\omega} - P^{ch}_{it\omega}) + LS_{t\omega} = D_t, \qquad \forall t \in 1, \cdots, \overline{T}, \forall \omega \in \Omega \tag{22}$$

Equation 8 acts as the budget constraint, ensuring that the total cost associated with various energy-related activities—such as investments, generation, market transactions, and load shedding—remains within the specified budget B. Equation 9 enforces load balance, requiring that the total power generated and exchanged within the system, including different types of units and interactions with the main grid, must match the load demand D_t for each time step t. Equations 10 and 11 set constraints on the maximum allowable power flow to and from the main grid at each time step, safeguarding against exceeding buying and selling power capacity. Equations 12 and 13 define the maximum allowable power generation from dispatchable units (G) and nondispatchable units (W) at each time step t, regulated by the investment decision x_i. Equations 14 and 15 govern the maximum allowable power generation and consumption by energy storage systems (S) while considering their efficiency (η_i) and the investment decision x_i. Equations 17 and 16 determine the feasibility of battery storage operations over time, ensuring charging occurs only if prior discharging falls within the system's efficiency and capacity bounds. Equations 18 to 20 control the state of each DER (x_i) and its ability to generate power based on whether x_i equals 1 (allowing generation) or 0 (prohibiting generation). Equation 21 imposes a limit on allowable load shedding ($LS_{t\omega}$), expressed as a percentage (ψ) of the load demand D_t, to prevent excessive load shedding and maintain system reliability. Finally, Equation 22 makes sure that after disruption, the MG can support the demands for the minimum $\overline{T}$ time steps. Collectively, these equations address various aspects of energy management, generation, and budget limitation within defined constraints and decision variables.

5. Results

5.1. Site Selection

Selecting an appropriate site for the implementation of a community microgrid is a critical step in achieving the objectives of improving financial, resiliency, and sustainability equity metrics. The effectiveness of CMGs are maximized when they are situated near neighborhoods that endure a high energy burden, especially in low-income regions. In this section, we describe the methodology employed to identify a suitable site for our community microgrid project in the Houston area, taking into account the demographic information provided by the Department of Energy's Low-income Energy Affordability Data (LEAD) tool. The LEAD tool provides comprehensive demographic information, including income levels and energy consumption patterns, for neighborhoods across Houston. It enables us to identify areas where residents may be experiencing a high energy burden.

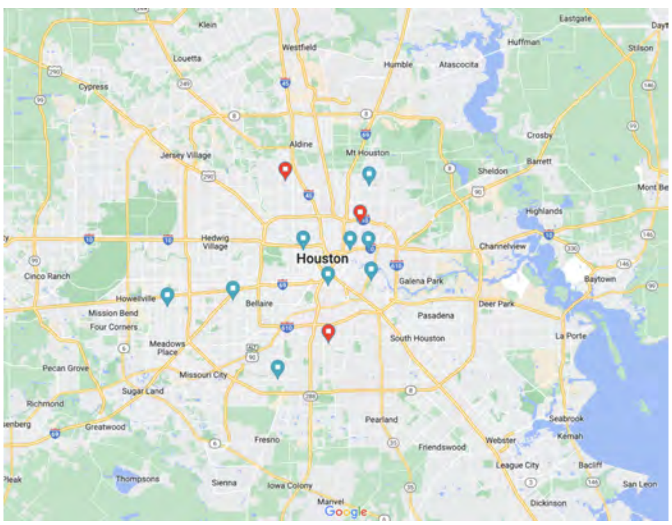

Figure 1: Multi service facility locations in the city of Houston

Figure 2: Selected multi service facility roof top area for solar pannels

Initially, we identified a list of 12 multi-service facilities in the Houston area that could potentially serve as the base for our microgrid project. These facilities were chosen based on their diverse service offerings and potential to benefit the local community.

Using the demographic data obtained from the LEAD tool, we conducted a proximity analysis to determine the distance between each candidate site and neighborhoods with a high energy burden. The analysis allowed us to prioritize sites that are in close proximity to these communities.

Table 6: The parameters of the three communities

	Geography ID	Energy Burden (%)	Avg. Annual Energy Cost ($)	Total Households
Community 1	48201230700	4	1784	962
Community 2	48201533302	4	1970	1233
Community 3	48201331400	6	1484	997

After a comprehensive evaluation of the 12 candidate sites in the Houston area, three sites emerged as the most suitable choice for our CMG implementation. These communities can be found in Figure 1 Also the data regarding each of these communities are gathered in Table 6. These sites not only demonstrated proximity to a low-income neighborhood facing a high energy burden but also exhibited strong community support and alignment with our research's objectives of improving financial, resiliency, and sustainability equity metrics.

Table 7: PV outputs obtained from PVWATTS website

Month	*Solar Radiation* (HWh/m^2/day)	*AC Energy* (kWh)
January	2.91	12,085
February	3.7	13,734
March	4.74	19.281
April	5.74	22,212
May	6.21	24,239
June	6.37	24,003
July	6.49	25,068
August	6.38	24,572
September	5.37	20,458
October	4.45	17,607
November	3.25	12,807
December	2.6	10,803
Annual	**4.85**	**226,869**

5.2. Numerical Results

Solving the proposed two-stage stochastic mixed-integer program presents two main computational challenges: (1) the large number of scenarios significantly increases the number of constraints, and (2) the presence of integer decision variables representing investments in distributed energy resources (DERs), energy storage systems, and solar panels increases the complexity of branching in conventional algorithms such as Branch and Bound. These characteristics typically lead to poor scalability, as the computational effort of solving mixed-integer programs can grow exponentially with problem size.

To address these challenges, we applied scenario reduction techniques [42] to decrease the number of constraints while maintaining uncertainty representation. We also employed Benders decomposition to separate the problem into a master problem containing only the integer variables and a subproblem that can be solved efficiently as a linear program.

In our study of how microgrids are set up in different communities, it's crucial to look at both the costs and how well the main parts of the MGs work. Table 8 shows how much money is needed for each technology used in MGs. This includes natural gas generators, battery storage units, and solar panels that use sunlight to make electricity. The table also shows how much electricity each technology can produce and store.

Table 8: MGs asset costs

		Natural Gas Generator	**Battery**	**Solar Panel**
Community 1	*Price*	\$750,000	\$350,000	\$210,840
	Capacity	2 MW	0.7 MWh	7185 MWh
Community 2	*Price*	\$750,000	\$750,000	\$541,800
	Capacity	2 MW	1.5 MWh	18461 MWh
Community 3	*Price*	\$750,000	\$250,000	\$468,160
	Capacity	2 MW	0.5 MWh	15966 MWh

Generators are provisioned with a capacity threshold aimed at satisfying a minimum of 90% of the aggregate energy requisition, thereby ensuring a consistent and resilient power supply in the face of fluctuating demand. Photovoltaic installations are comprised of 280-watt panels, with the selection predicated upon local solar irradiance levels averaging 5.2 kWh/m^2/day. The resultant solar energy yield, calculated via the PVWATTS portal, reflects an optimization process that considers the available rooftop expanse of communal multi-service structures as a determinant of potential energy capture.

Battery storage specifications are predicated on maintaining a reserve of 25% of the assessed peak electrical load, which in turn is ascertained through the application of a 0.6 load factor—a heuristic that correlates the average load to peak load conditions. This strategic sizing of battery storage is intended to balance the dual imperatives of ensuring energy availability during peak demand intervals and economic efficiency by circumventing the capital and operational costs associated with overcapacity.

We have two sets of stochastic variables: renewable generation forecasts and power outage probabilities. Random values for each time step for these variables are generated using historical data and normal probability distribution functions. To capture these uncertainties, 25 scenarios for each variable are created using Latin Hypercube Sampling. To manage computational complexity while ensuring accuracy, scenario reduction is performed with the GAMS SCENRED tool [42].

Setting up microgrid (MG) systems is customized for each community based on how much energy they use, what kind of infrastructure they have, and their budget limits. The initial information collected helps us later analyze how the MGs affect each community's costs, pollution levels, and ability to recover from disruptions.

Table 9: Summary of the Cases

Cases	**DER**	**NonDER + Storage System**	**Budget**	**Scenario Names**
Base Case	-	-	-	Base Case
Case 1	✓	✓	Unlimited	DER Rx1Bx1 FB
Case 2	-	✓	Unlimited	NDER Rx1Bx1 FB
Case 3	✓	✓	$400,000	DER Rx1Bx1 LB1
Case 4	✓	✓	$1,000,000	DER Rx1Bx1 LB2
Case 5	✓	✓	$4,000,000	DER Rx1Bx1 LB3
Case 6	-	✓	$400,000	NDER Rx1Bx1 LB1
Case 7	-	✓	$1,000,000	NDER Rx1Bx1 LB2
Case 8	-	✓	$4,000,000	NDER Rx1Bx1 LB3
Case 9	✓	✓(×3)	Unlimited	DER Rx3Bx3 FB
Case 10	-	✓(×3)	Unlimited	NDER Rx3Bx3 FB
Case 11	✓	✓(×3)	$400,000	DER Rx3Bx3 LB1
Case 12	✓	✓(×3)	$1,000,000	DER Rx3Bx3 LB2
Case 13	✓	✓(×3)	$4,000,000	DER Rx3Bx3 LB3
Case 14	-	✓(×3)	$400,000	NDER Rx3Bx3 LB1
Case 15	-	✓(×3)	$1,000,000	NDER Rx3Bx3 LB2
Case 16	-	✓(×3)	$4,000,000	NDER Rx3Bx3 LB3

In our comprehensive exploration of Community Microgrid (CMG) implementations detailed in Table 9, we have delineated the characteristics of each case to understand their impact on community energy profiles. Each case is defined by the presence or absence of key components and the budget available, which collectively determine the scope and scale of CMG deployment.

The first column in the table represents dispatchable energy resources (DER). A (✓) indicates that the respective case incorporates DER. Conversely, a (-) signifies the absence of DER, implying reliance on only power storage systems or renewable solutions. We call the latter cases, NDER cases.

The second column denotes the presence of storage systems (SS) and non-dispatchable energy resources (Non-DER). A (-) here indicates that the case does not include any form of SS or Non-DER generation capabilities. A (✓) signifies that the case includes SS and Non-DER generators as per the capacities outlined in Table 8. Moreover, a (✓) followed by ($\times 3$) indicates that these capacities are enhanced to three times the standard level, reflecting a scenario with significantly expanded storage and generation capabilities.From now on, we will refer to the cases with the original capacity of Non-DER and SS as Rx1Bx1, and the cases with the capacities of SS and Non-DER expanded three times as Rx3Bx3.

The third column specifies the budget allocated for each case. This parameter dictates the extent to which the CMG components can be implemented, ranging from limited-budget scenarios to those with ample financial resources for comprehensive CMG development. Terms FB, LB1, LB2, and LB3 stand for full budget, limited budget scenario 1, limited budget scenario 2, and limited budget scenario 3 respectively.

Cases highlighted in bold font have been discussed in detail from sections 5.2.1 to 5.2.5, where we delve into the nuances of each case's impact on the community energy metrics. For those interested in the outcomes of other cases, the results have been conveniently compiled in the appendix. This structured approach allows us to assess the effect of varying configurations and investment levels on the CMG's ability to enhance energy sustainability, financial viability, and resiliency within the communities.

All computations were carried out in GAMS version 44.2.0 on a high-performance server equipped with dual Intel Xeon E5-2690 v2 CPUs (40 threads) and 377 GB RAM. Table 10 presents the average computation time for each test case. The results, ranging from approximately 45 seconds to 542 seconds depending on the budget constraint, demonstrate that the proposed planning framework is computationally tractable for realistic community microgrid design. However, further algorithmic enhancements may be needed to ensure scalability to significantly larger systems.

Table 10: Average Solving Time for Each Case (averaging over all communities)

Case Number	Average Solving Time (s)	Case Number	Average Solving Time (s)
Case 1	119.24	**Case 9**	135.66
Case 2	53.38	**Case 10**	60.01
Case 3	315.89	**Case 11**	44.49
Case 4	158.93	**Case 12**	556.88
Case 5	375.37	**Case 13**	260.77
Case 6	411.34	**Case 14**	45.14
Case 7	166.17	**Case 15**	527.60
Case 8	55.75	**Case 16**	59.87

5.2.1. Base Case (No MG)

The base case depicted in the table 11 serves as a representation of the existing energy infrastructure and management in three different communities, designated as Community 1, Community 2, and Community 3. The data illustrate several critical aspects of these communities' current energy profiles before the implementation of community microgrids (CMGs).

Firstly, the numbers under "Power Bought From the Grid" for each community indicate the total electricity demand that is met exclusively by purchasing from the main grid, highlighting the communities' reliance on external power sources. The absence of any figures under "Power Sold to the Grid" underscores a key limitation in the current setup: there is no infrastructure or capability for these communities to generate their own power and, consequently, no opportunity to contribute electricity back to the grid.

The "Load Shedding" figures represent the amount of power (in kilowatts) that is not served due to grid outages or insufficient grid capacity. These figures reflect the vulnerability of the communities to power interruptions and the lack of local energy resources to bridge the gap during such events.

The zeros recorded for DER (Distributed Energy Resources), NonDER, Charge, and Discharge

Table 11: Base Case output variables across all communities

Parameter	Community 1	Community 2	Community 3
Power Bought From the Grid (MWh)	132354	187286.4	114152.4
Power Sold to the Grid (MWh)	0	0	0
Load Shedding (MWh)	2914.39	4123.98	2513.6
DER (MWh)	0	0	0
NonDER (MWh)	0	0	0
Charge (MWh)	0	0	0
Discharge (MWh)	0	0	0
Total Demand (MWh)	132354	187286.4	114152.4
CESI	0.207	0.156	0.232
CEFI	0.5	0.5	0.5
CERI	0.489	0.489	0.489
Carbon Emission (lbs)	56912.22	80533.15	49085.53
Power Cost ($)	222703.32	314887.03	191938.57

signify the non-existence of local generation or storage assets, such as solar panels, wind turbines, or batteries, that would typically constitute a microgrid's infrastructure. This lack of local energy assets results in a total absence of self-generated power, energy storage, and the subsequent capability to manage energy supply and demand within the community.

The total demand for each community is a summation of all the electricity requirements that must be met, highlighting the scale of dependence on the main grid. The indices—$CESI$, $CEFI$, and $CERI$—reflect the communities' energy sustainability, financial, and resiliency statuses, respectively. These indices are calculated based on the current energy setup and will serve as a benchmark for assessing the impact of CMGs in subsequent analyses.

Finally, the ”Emission” and ”Power Cost” rows quantify the environmental and economic impacts of the current energy model. The emissions data indicate the environmental burden of the communities' energy consumption, while the power cost provides a financial assessment of the energy being purchased from the grid. These figures lay the groundwork for understanding the potential benefits that CMGs could offer in terms of sustainability, financial savings, and resilience, particularly for low-income, high-burden areas.

5.2.2. Case 1: Community with MG (with DER, No Budget Limitation)

The implementation of Community Microgrids (CMGs) has significantly transformed the energy landscape of the three studied communities, as evidenced by the data in Table 12. One of the most remarkable outcomes is the substantial reduction in power purchased from the main grid. This reduction is not only indicative of decreased dependency on external power sources but also an important factor in enhancing the communities' energy resilience. The ability to sustain power during grid outages or peak demand times is a direct reflection of increased self-sufficiency brought about by CMGs.

Concurrently, there is a noteworthy increase in the power sold to the main grid, which suggests that the communities are now capable of generating surplus energy. This surplus, in turn, can be monetized, providing a new revenue stream that contributes to the communities' financial independence and sustainability.

Table 12: Case 1 Output variables across all communities

Parameter	**Community 1**	**Community 2**	**Community 3**
Power Bought From the Grid (MWh)	0	919.4	351.78
Power Sold to the Grid (MWh)	3229.67	1427.49	2782.46
Load Shedding (MWh)	0	0	0
DER (MWh)	128390.29	169501.12	100621.14
NonDER (MWh)	7185.29	18461.07	15966.83
Charge (MWh)	17.1	1291.32	14.46
Discharge (MWh)	9	1433.41	6.07
Total Demand (MWh)	132354	187286.4	114152.4
CEI	0.702	0.710	0.718
CESI	0.619	0.62	0.663
CEFI	0.888	0.87	0.915
CERI	0.598	0.64	0.576
Carbon Emission (lbs)	27335.58	36472.81	21568.8
Power Cost ($)	49747.24	80386.74	32530.11

Also, in Table 12, we observe varying interactions with the main grid across the three communities studied. Notably, Community 1 does not purchase power from the main grid, whereas Communities 2 and 3 do engage in both buying and selling electricity to and from the grid.

For Community 1, the absence of power purchases from the main grid is attributed to the sufficient generation capacity within the community itself. The combination of DER and renewable sources is adequate to fulfill the total demand, thus eliminating the need to draw power from the external grid. This self-sufficiency bolsters the community's resilience, ensuring that power needs are met even in the event of main grid outages. Moreover, this approach enhances sustainability by utilizing clean energy sources and improves financial metrics by reducing reliance on externally priced energy. The model's strategy for battery usage in Community 1 is conservative, with charging primarily reserved for ensuring uninterrupted power during outages, rather than for regular cycling, which aligns with the goal of enhancing resiliency.

In contrast, Communities 2 and 3 exhibit both power purchases from and sales to the main grid. This indicates that there are periods within the time horizon studied where the combined power generation from DER and renewable sources is insufficient to meet the demand. To address this, the model strategically opts to buy power from the grid and discharge the batteries during times when internal generation falls short. This decision is made to ensure that the communities' energy needs are met with the best possible balance of resilience and sustainability. The model takes into account the fluctuating nature of renewable energy production and the communities' demand patterns to optimize power sourcing decisions, hence the observed combination of buying and selling activities.

Community 2, despite having power sold to the grid, still needs to purchase electricity at certain times, which can be due to the intermittency of renewable energy sources or peaks in demand that exceed the current generation and storage capacity. Similarly, Community 3 engages in these transactions to maintain a stable and resilient energy supply, reflecting a calculated approach to maximize the benefits of the CMG while navigating the limitations of available generation capacity and storage.

Another crucial aspect is the elimination of load shedding. The absence of load shedding signifies a more reliable and equitable energy supply across different neighborhoods. This improvement in service quality is a step towards addressing energy equity issues, particularly in low-income, high-burden areas that are more susceptible to the adverse effects of power outages.

Table 13 demonstrates the substantial enhancements in key energy equity metrics. The $CESI$, $CEFI$, and $CERI$ show dramatic improvements, with increases of 199%, 78%, and 22% for Community 1; 297%, 74%, and 31% for Community 2; and 186%, 83%, and 18% for Community 3, respectively. These metrics underline the significant strides made towards achieving a more sustainable, financially viable, and resilient energy system within the communities.

Emissions have also decreased considerably, with reductions of 52%, 55%, and 56% for Communities 1, 2, and 3, respectively. This drop in emissions is a clear indicator of the environmental benefits of CMGs, contributing to a reduction in the communities' carbon footprint and aligning with broader goals of climate change mitigation.

Lastly, the improvements in energy generation costs, which have decreased by 76%, 74%, and 83% for the respective communities, are indicative of the economic advantages of CMGs. These cost savings can have a significant impact on the affordability of energy for residents, especially in under-served areas, thereby enhancing the financial equity of the communities.

The aggregate effect of CMGs on these communities underscores the potential of decentralized energy resources in transforming energy systems to be more equitable, resilient, and sustainable, especially in regions that are traditionally under-served by the main grid.

Table 13: Case 1 outputs improvement across all communities

Parameter	**Community 1**	**Community 2**	**Community 3**
CEI	76%	86%	76%
CESI	199%	297%	186%
CEFI	78%	74%	83%
CERI	22%	31%	18%
Carbon Emission (lbs)	-52%	-55%	-56%
Power Cost ($)	-78%	-74%	-83

5.2.3. Case 2: Community MG (with renewable and batteries, without DER, No Budget Limitation)

The implementation of Community Microgrids (CMGs), even in scenarios where Distributed Energy Resources (DER) are not viable, demonstrates significant positive impacts on community energy profiles, as detailed in Table 14. In this scenario, the communities leverage solar panels and energy storage systems, such as batteries installed on residential rooftops and garages, to enhance their energy systems.

Despite the absence of DER power sources like wind or biomass, the 'Power Bought From the Grid' shows a high consumption of energy from the main grid, reflecting the sole reliance on traditional energy procurement methods. However, 'Power Sold to the Grid' remains at zero because the focus is on utilizing all generated power within the community, accounting for the lack of surplus energy to sell back to the grid.

Notably, load shedding is nonexistent, indicating that the implemented CMG, with its solar panels and storage systems, effectively meets the demand and mitigates any potential outages or disruptions from the main grid. This marks a considerable improvement in the quality and reliability of power supply within the communities.

Table 14: Case 2 variable outputs across all communities

Parameter	**Community 1**	**Community 2**	**Community 3**
Power Bought From the Grid (MWh)	127991.85	172722.51	100350.01
Power Sold to the Grid (MWh)	0	0	0
Load Shedding (MWh)	0	0	0
DER (MWh)	0	0	0
NonDER (MWh)	7185.29	18461.07	15966.83
Charge (MWh)	576.02	1568.93	14.43
Discharge (MWh)	630.02	1733.25	6.03
Total Demand (MWh)	132354	187286.4	114152.4
CEI	0.454	0.470	0.490
CESI	0.25	0.238	0.34
CEFI	0.525	0.545	0.564
CERI	0.587	0.628	0.566
Carbon Emission (lbs)	53845.77	72665.55	42216.18
Power Cost ($)	211506.797	286691.8	167304.68

The indices in Table 15 reflect the effectiveness of the CMG strategy that relies on solar power and storage. The $CESI$, $CEFI$, and $CERI$ have shown substantial improvements, with $CESI$ increasing by 21%, 53%, and 47%, $CEFI$ by 5%, 9%, and 13% and $CERI$ by 20%, 28%, and 16% for the respective communities. These gains underscore the potential for CMGs to significantly bolster both the sustainability and resilience of community energy systems.

The reductions in emissions are also notable, with Communities 1, 2, and 3 experiencing decreases of 5%, 10%, and 14% respectively. This reduction aligns with global efforts to decrease carbon footprints and combat climate change.

Finally, the financial benefits of CMGs are evident in the reduced energy generation costs, with declines of 5%, 9%, and 13% for the respective communities. These cost savings can be particularly impactful for low-income residents, demonstrating that CMGs can provide financial relief alongside environmental benefits.

In conclusion, the data from Tables 14 and 15 show that CMGs with only solar panels and energy storage can still substantially improve energy sustainability, financial indices, and resiliency for communities. These improvements are crucial for areas where installing diverse DERs may not be feasible, yet the desire for enhanced energy equity and sustainability remains a priority.

Table 15: Case 2 variables improvement across all communities

Parameter	**Community 1**	**Community 2**	**Community 3**
CEI	14%	23%	20%
CESI	21%	53%	47%
CEFI	5%	9%	13%
CERI	20%	28%	16%
Carbon Emission (lbs)	-5%	-10%	-14%
Power Cost ($)	-5%	-9%	-13%

5.2.4. Cases 3,4, and 5: Community MG with limited budget, renewable and batteries, and DER

In this section of our analysis, we delve into the effects of limited budget scenarios on CMG implementation within Community 2. The three budget scenarios, designated as LB1, LB2, and LB3, correspond to budgets of $400,000, $1,000,000, and $4,000,000 respectively. These scenarios provide insight into the strategic allocation of funds under constrained financial resources and highlight the impact of incremental investments on community energy indices.

As indicated in the results summarized in Table 16, in the most constrained budget scenario LB1, the model prioritizes investment in battery storage systems. This decision underscores the emphasis on enhancing the community's energy resiliency, which is reflected in a 19% improvement in the $CERI$. The prioritization of batteries can be attributed to their role in stabilizing the local grid and ensuring a consistent power supply, especially during outages or peak demand periods.

With an increased budget in scenario LB2, the model allocates funds toward the installation of renewable energy generators. This investment yields a notable improvement in the $CESI$ by 27%, demonstrating the community's transition towards more sustainable energy sources. Additionally, the $CERI$ sees a further enhancement of 28%, indicating a strengthened energy system capable of withstanding and quickly recovering from disruptions.

In the most generous budget scenario LB3, the model opts to invest in DER. The outcomes of this scenario approach the performance of a no-budget-limitation scenario for Community 2, as detailed in Table 12. The adoption of DER represents the final step towards a fully realized CMG system, achieving a near-optimal energy profile for the community.

Table 16: Case 3, 4, and 5 output variables for Community 2

Parameter	**Case 3 (LB1)**	**Case 4 (LB2)**	**Case 5 (LB3)**
Power Bought From the Grid (MWh)	191563.5	181790.39	14341.14
Power Sold to the Grid (MWh)	0	0	9.56
Load Shedding (MWh)	0	0	0
DER (MWh)	0	0	154925.96
NonDER (MWh)	0	9577.32	18461.07
Charge (MWh)	1407.8	1568.93	1075.45
Discharge (MWh)	1557.56	1733.25	1190.18
Total Demand (MWh)	187286.4	187286.4	187286.4
CEI	0.413	0.448	0.684
CESI	0.16	0.198	0.591
CEFI	0.5	0.519	0.825
CERI	0.58	0.628	0.637
Carbon Emission (lbs)	80597.55	76485.57	39015.46
Power Cost ($)	315088.2	302903.15	110092.28

The corresponding improvements across the indices in Table 17 are particularly significant. For LB3, the $CESI$ soars by 279%, indicating a drastic shift towards energy sustainability. The financial benefits are also substantial, with the $CEFI$ improving by 65%, and the overall power costs reducing by 65%. These financial improvements suggest that CMGs not only promote energy independence but also offer long-term economic benefits.

It is important to note that while the CMG outputs in the no-budget-limitation scenario are slightly better, the results from the limited budget scenarios underscore the efficacy of strategic investments. Even with financial constraints, the CMG can still provide significant enhancements to the community's energy profile.

In conclusion, this analysis illustrates that even under limited budget scenarios, strategic investments in CMG components such as batteries and renewable generators can lead to substantial improvements in energy resiliency, sustainability, and financial metrics for the community. This finding is crucial for policymakers and community planners, especially when considering CMG implementations in areas with limited financial resources.

5.2.5. Case 9: Expanding Renewable and Batteries with DER and no budget limitation

In this section, we explore a scenario where expansion opportunities for CMGs are abundant, allowing for a significant scale-up in renewable energy and battery storage capacity. This scenario assumes that multi-service facilities are available for building out the MG infrastructure and that

Table 17: Cases 3, 4, and 5 output variables improvement for Community 2

Parameter	**Case 3 (LB1)**	**Case 4 (LB2)**	**Case 5 (LB3)**
CEI	8%	17%	79%
CESI	3%	27%	279%
CEFI	0%	4%	65%
CERI	19%	28%	30%
Carbon Emission (lbs)	0%	-5%	-52%
Power Cost ($)	0%	-4%	-65%

residents are incentivized to contribute to the capacity of the CMG by installing solar panels and batteries. Consequently, the renewable energy and battery storage capacities for the MGs have been tripled.

The outcomes of this expansion are illustrated in the results summarized in table 18. The 'Power Bought From the Grid' has drastically reduced for all communities, with Community 3 buying only a nominal amount, which signifies a massive shift towards energy self-sufficiency. Moreover, the 'Power Sold to the Grid' has increased for all communities, indicating an excess generation capacity that can be monetized, contributing positively to the communities' economies.

Load shedding is virtually eliminated across all communities, which is indicative of a reliable power supply that can meet the communities' demands without interruption. This reliability is paramount in ensuring equitable energy access and improving the quality of life for residents.

When examining the energy indices, there are substantial improvements across all metrics. The improvements are summarized in table 19 The CEI shows improvements of 96%, 120%, and 99% for Communities 1, 2, and 3, respectively, indicating a near-doubling of community engagement and satisfaction with the energy system. The $CESI$ has seen tremendous increases, with Community 2 achieving a 342% improvement, showcasing a deep commitment to renewable energy sources and a reduced carbon footprint.

Financially, the $CEFI$ has also seen significant enhancements, with increases of 79%, 82%, and 90%, indicating improved economic outcomes for the communities due to reduced operational costs and increased revenue from energy sales. This economic upliftment is a critical factor in ensuring the long-term viability of the CMGs.

The $CERI$ improvements of 62%, 88%, and 49% further underscore the enhanced ability of the communities to withstand and adapt to energy disruptions or fluctuations in demand. This

Table 18: Case 9 output variables across all communities

Parameter	Community 1	Community 2	Community 3
Power Bought From the Grid (MWh)	0	0.17	62.48
Power Sold to the Grid (MWh)	2224.08	2955.38	3362.71
Load Shedding (MWh)	0	0	0
DER (MWh)	117653.88	139323.48	74441.5
NonDER (MWh)	16933.2	50955.18	43180.63
Charge (MWh)	18	27.15	1407.71
Discharge (MWh)	27	64.21	1574.36
Total Demand (MWh)	132354	187286.4	114152.4
CEI	0.780	0.840	0.810
CESI	0.651	0.69	0.752
CEFI	0.894	0.91	0.949
CERI	0.794	0.92	0.728
Carbon Emission (lbs)	25049.69	29663.43	15874.98
Power Cost ($)	47012.432	57483.03	19513.83

resilience is particularly important in the face of climate change and extreme weather events.

Emissions have also been dramatically reduced, with reductions of 56%, 63%, and 68% for the respective communities. These reductions contribute to global efforts to mitigate climate change and improve local air quality.

The overall power costs show remarkable decreases of 79%, 82%, and 90%, translating into significant savings for the communities and individuals, thereby supporting energy equity and affordability.

In summary, this expansion scenario without a limited budget is the most successful of all, as it provides the best results in terms of sustainability, financial metrics, and resiliency. The detailed comparisons of this scenario with the LB1, LB2, and LB3 scenarios are provided in the appendix. This analysis clearly demonstrates that with the right incentives and opportunities, CMGs can be effectively scaled to maximize their potential benefits, offering a robust solution to the challenges of modern energy systems.

5.3. Effect of Electricity Price Change

To evaluate the robustness of our equity-based planning framework under market fluctuations, we conducted two additional experiments focused on electricity price volatility and its economic impact. In the first scenario, we modeled a 50% increase in electricity prices, accompanied by a 10% reduction in demand. Results show that $CEFI$ improves in all configurations, reflecting

Table 19: Case 9 output variables improvement across all communities

Parameter	Community 1	Community 2	Community 3
CEI	96%	120%	99%
CESI	214%	342%	224%
CEFI	79%	82%	90%
CERI	62%	88%	49%
Carbon Emission (lbs)	-56%	-63%	-68%
Power Cost ($)	-79%	-82%	-90%

the increased relative value of locally generated DER power. For example, in case 1, $CEFI$ rose from 0.87 (table 12) to 0.925 (table 20), and in the case 9, from 0.91 (table 18) to 0.954 (table 21). Meanwhile, $CESI$ and $CERI$ remained stable or slightly improved, indicating strong environmental and resiliency performance even under higher cost pressures. These results suggest that microgrids with sufficient DER capacity not only reduce dependency on the main grid but also insulate communities from price shocks and deliver higher financial and operational equity.

The second scenario reversed the trend: a 50% price drop with a 10% demand increase. Interestingly, $CEFI$ declined in several DER scenarios despite the lower cost of electricity, for instance, falling from 0.87 (table 12) to 0.719 (table 22) in case1 and from 0.91 (table 18) to 0.769 (table 23) in case 9. This counterintuitive outcome is explained by two factors. First, we assume DER generation costs remain fixed over the time horizon, as they are typically determined at the time of installation. Second, higher demand results in increased reliance on the grid, making the fixed cost of DER less financially favorable in a relative sense. Importantly, $CEFI$ is a normalized index between 0 and 1, and a lower value does not necessarily indicate a higher absolute cost for the community. It reflects a relative shift in affordability within the modeled framework. $CERI$ remained almost unchanged, showing resiliency is infrastructure-driven, while $CESI$ decreased slightly due to increased emissions from greater total energy consumption.

It is worth mentioning that in both scenarios, when electricity prices increase by 50% or decrease by 50%, Case 1 and Case 9 (communities with microgrids installed) consistently perform better than the base case (community without a microgrid). This sensitivity analysis can be summarized as follows: The installation of microgrids improves the three equity indices in the communities. However, when electricity prices are high, microgrids provide even greater financial benefits. This is mainly because they give communities the opportunity to sell excess power back to the grid with higher prices. It also confirms that $CEFI$ is responsive to price changes and demand changes, while $CERI$ and $CESI$ are more strongly governed by the investment in infrastructure and the mix of technology. These findings underscore the importance of prioritizing the integration of DER to strengthen the financial equity of energy systems in under-served communities.

Table 20: Cases 1–8 comparison of output variables under 50% electricity price increase scenario for community 2

Parameter	**Case 1**	**Case 2**	**Case 3**	**Case 6**	**Case 4**	**Case 7**	**Case 5**	**Case 8**
CESI	0.63	0.26	0.17	0.17	0.26	0.26	0.62	0.26
CEFI	0.93	0.55	0.50	0.50	0.55	0.55	0.89	0.55
CERI	0.65	0.64	0.59	0.59	0.59	0.59	0.65	0.64

Table 21: Cases 9–16 comparison of output variables under 50% electricity price increase scenario for community 2

Parameter	**Case 9**	**Case 10**	**Case 11**	**Case 14**	**Case 12**	**Case 15**	**Case 13**	**Case 16**
CESI	0.70	0.42	0.31	0.31	0.42	0.42	0.70	0.42
CEFI	0.95	0.64	0.56	0.56	0.64	0.64	0.94	0.64
CERI	0.96	0.95	0.49	0.49	0.49	0.49	0.81	0.95

Table 22: Cases 1–8 comparison of output variables under 50% electricity price decrease scenario for community 2

Parameter	**Case 1**	**Case 2**	**Case 3**	**Case 6**	**Case 4**	**Case 7**	**Case 5**	**Case 8**
CESI	0.61	0.22	0.14	0.14	0.18	0.18	0.56	0.22
CEFI	0.72	0.54	0.50	0.50	0.52	0.52	0.69	0.54
CERI	0.63	0.62	0.57	0.57	0.62	0.62	0.62	0.62

Table 23: Cases 9–16 comparison of output variables under 50% electricity price decrease scenario for community 2

Parameter	**Case 9**	**Case 10**	**Case 11**	**Case 14**	**Case 12**	**Case 15**	**Case 13**	**Case 16**
CESI	0.68	0.36	0.26	0.26	0.36	0.36	0.65	0.36
CEFI	0.77	0.61	0.55	0.55	0.61	0.61	0.76	0.61
CERI	0.88	0.87	0.49	0.49	0.49	0.49	0.75	0.87

5.4. Summary of Numerical Results

This subsection summarizes the key findings from the numerical results of various CMG scenarios. The base case analysis, without CMGs, highlighted the communities' reliance on external power sources, resulting in significant load shedding and high emissions. The introduction of CMGs with DER and no budget limitations (Case 1) demonstrated substantial reductions in power purchases from the grid, elimination of load shedding, and significant improvements in key energy equity metrics, such as $CESI$, $CEFI$, $CERI$. For instance, Community 1 became completely independent of the main grid. Meanwhile, Communities 2 and 3 had more than a 99% reduction in the dependency on the main grid. Also, the overall CEI improved 76%, 86%, and 76% for communities 1, 2, and 3 respectively.

In scenarios with solar panels and energy storage systems without DER (Case 2), the communities showed notable improvements in energy sustainability and resiliency, despite continued reliance on grid power. CEI improved 14%, 23%, and 20% for communities 1, 2, and 3 respectively. Limited budget scenarios (Cases 3, 4, and 5) revealed a strategic prioritization in CMG investments. Initially, energy storage systems were prioritized to enhance resiliency, followed by renewable energy sources, and lastly, gas generators, resulting in incremental improvements in energy equity metrics even under financial constraints.

The most expansive scenario (Case 9), with abundant opportunities for scaling up renewable energy and battery storage, showed the highest improvements across all metrics. This scenario achieved near-total energy self-sufficiency, substantial increases in $CESI$, $CEFI$, and $CERI$, and dramatic reductions in emissions and power costs, underscoring the transformative potential of fully realized CMGs. CEI improved by 96%, 120% and 99% in communities 1, 2, and 3 respectively.

In addition to the base and budget-limited scenarios, we also evaluated the impact of electricity price fluctuations on equity outcomes. When prices increased by 50% and demand dropped slightly, $CEFI$ improved across all cases, showing the value of local DER generation under high-cost conditions. In contrast, a 50% price decrease paired with higher demand led to lower $CEFI$ values in some cases, highlighting how fixed DER costs may appear less favorable when grid electricity becomes cheaper. Importantly, $CERI$ remained stable, and $CESI$ showed only modest variation, reinforcing the robustness of CMG designs even under market uncertainty.

The numerical results highlight the significant benefits of CMGs in enhancing energy sustainability, financial viability, and resiliency, particularly in under-served communities. The findings also emphasize the importance of strategic investments in energy storage and renewable resources to maximize these benefits, even under budget constraints.

6. Conclusion

Our investigation into CMGs in Houston's energy-poverty neighborhoods has demonstrated the technology's significant impact on enhancing energy equity. By implementing CMGs based on multi-service facilities, we have observed significant improvements in the $CESI$, $CEFI$, and $CERI$, which were developed as part of this study. These improvements were consistent across various scenarios, including those with budget constraints, lack of diverse DER, and enhanced capacity through increased renewable and storage systems. Notably, the most significant enhancements were seen in the scenario that combined an unrestricted budget with the inclusion of DER and a tripling of renewable and battery capacities, indicating the high potential of well-resourced CMGs. However, even limited-budget scenarios showed that strategic investments could yield substantial benefits, suggesting that CMGs are a versatile solution adaptable to different financial and technical constraints.

Our research provides a clear indication that CMGs can be a cornerstone for sustainable urban development, promoting energy independence, financial savings, and resilience against power disruptions. The case for CMGs is strong, advocating for policy and community support to scale these solutions across urban landscapes, thereby leading to a more equitable and sustainable energy future for city neighborhoods.

Building upon the equity-centered microgrid planning framework presented in this study, several promising research directions can be pursued to further enhance the impact and applicability of the approach. First, integrating cooperative game theory models, such as Shapley value-based or core allocations, could provide systematic methods for fairly distributing costs and benefits among diverse community stakeholders, thereby strengthening procedural and distributive justice dimensions. Second, future work can explore the deployment of networked community microgrids that facilitate inter-community energy sharing and infrastructure coordination. Studying such interconnected systems under uncertainty may reveal new dynamics in resilience, resource allocation, and equity at regional scales, particularly in urban and peri-urban settings. Third, expanding the equity evaluation framework to incorporate social metrics including community participation levels, governance inclusivity, and social capital indices, would enable a more holistic and multidimensional assessment of microgrid impacts beyond technical and financial outcomes. Finally, applying and validating the proposed framework in diverse geographical and socio-economic contexts, such as remote, indigenous, and climate-vulnerable communities, can test its robustness, uncover context-specific equity challenges, and inform the development of adaptable, culturally sensitive planning methodologies. In parallel, exploring computational advances such as machine learning-driven scenario generation or distributed optimization methods could also enhance scalability and real-time decision-making capabilities for large-scale community energy systems.

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Declaration of AI Assistance

During the preparation of this work, the authors utilized ChatGPT to enhance the readability and writing quality of the manuscript. After employing this AI tool, the authors thoroughly reviewed and edited the content to ensure its accuracy and integrity. The authors take full responsibility for the final content of the published article.

References

[1] Palit D, Chaurey A. Off-grid rural electrification experiences from South Asia: Status and best practices. Energy for sustainable development. 2011;15(3):266-76.

[2] Hatziargyriou N, Asano H, Iravani R, Marnay C. Microgrids. IEEE power and energy magazine. 2007;5(4):78-94.

[3] Javadi MS. Unlocking responsive flexibility within local energy communities in the presence of grid-scale batteries. Sustainable Cities and Society. 2024;114:105697.

[4] Parise G, Parise L, Martirano L, Chavdarian PB, Su CL, Ferrante A. Wise port and business energy management: Port facilities, electrical power distribution. IEEE Transactions on Industry Applications. 2015;52(1):18-24.

[5] Warneryd M, Håkansson M, Karltorp K. Unpacking the complexity of community microgrids: A review of institutions' roles for development of microgrids. Renewable and Sustainable Energy Reviews. 2020;121:109690.

[6] Gui EM, Diesendorf M, MacGill I. Distributed energy infrastructure paradigm: Community microgrids in a new institutional economics context. Renewable and Sustainable Energy Reviews. 2017;72:1355-65.

[7] Hernández D. Understanding 'energy insecurity'and why it matters to health. Social science & medicine. 2016;167:1-10.

[8] Parag Y, Ainspan M. Sustainable microgrids: Economic, environmental and social costs and benefits of microgrid deployment. Energy for Sustainable Development. 2019;52:72-81.

[9] Adefarati T, Bansal RC. Reliability, economic and environmental analysis of a microgrid system in the presence of renewable energy resources. Applied energy. 2019;236:1089-114.

[10] Zhang W, Valencia A, Gu L, Zheng QP, Chang NB. Integrating emerging and existing renewable energy technologies into a community-scale microgrid in an energy-water nexus for resilience improvement. Applied Energy. 2020;279:115716.

[11] Wu L, Ortmeyer T, Li J. The community microgrid distribution system of the future. The Electricity Journal. 2016;29(10):16-21.

[12] Duan Y, Li L, Jordehi AR, Tostado-Véliz M, Safaraliev M. A hierarchical framework for integration of smart buildings in fully-renewable multi-microgrids and distribution systems: towards more sustainable societies. Sustainable Cities and Society. 2024;115:105800.

[13] Min Y, Lee HW. Quantifying clean energy justice: Impact of Solarize programs on rooftop solar disparities in the Pacific Northwest. Sustainable Cities and Society. 2024;104:105287.

[14] Raman G, Yang Y, Peng JCH. The social factors shaping community microgrid operation. Nature Communications. 2024;15(1):6451.

[15] Syed MM, Morrison GM. A rapid review on community connected microgrids. Sustainability. 2021;13(12):6753.

[16] Akter A, Zafir EI, Dana NH, Joysoyal R, Sarker SK, Li L, et al. A review on microgrid optimization with meta-heuristic techniques: Scopes, trends and recommendation. Energy Strategy Reviews. 2024;51:101298.

[17] Das A, Ni Z. A computationally efficient optimization approach for battery systems in islanded microgrid. IEEE Transactions on Smart Grid. 2017;9(6):6489-99.

[18] Cornélusse B, Savelli I, Paoletti S, Giannitrapani A, Vicino A. A community microgrid architecture with an internal local market. Applied Energy. 2019;242:547-60.

[19] Hafiz F, de Queiroz AR, Fajri P, Husain I. Energy management and optimal storage sizing for a shared community: A multi-stage stochastic programming approach. Applied energy. 2019;236:42-54.

[20] Papari B, Edrington CS, Ghadamyari M, Ansari M, Ozkan G, Chowdhury B. Metrics analysis framework of control and management system for resilient connected community microgrids. IEEE Transactions on Sustainable Energy. 2021;13(2):704-14.

[21] Tomin N, Shakirov V, Kozlov A, Sidorov D, Kurbatsky V, Rehtanz C, et al. Design and optimal energy management of community microgrids with flexible renewable energy sources. Renewable Energy. 2022;183:903-21.

[22] Aziz M, Dagdougui H, Elhallaoui I. A decentralized game theoretic approach for virtual storage system aggregation in a residential community. IEEE Access. 2022;10:34846-57.

[23] Gholami M, Muyeen S, Lin S. Optimizing microgrid efficiency: Coordinating commercial and residential demand patterns with shared battery energy storage. Journal of Energy Storage. 2024;88:111485.

[24] Rodrigues SD, Garcia VJ. Transactive energy in microgrid communities: A systematic review. Renewable and Sustainable Energy Reviews. 2023;171:112999.

[25] Liu G, Jiang T, Ollis TB, Zhang X, Tomsovic K. Distributed energy management for community microgrids considering network operational constraints and building thermal dynamics. Applied energy. 2019;239:83-95.

[26] Bokkisam HR, Singh S, Acharya RM, Selvan M. Blockchain-based peer-to-peer transactive energy system for community microgrid with demand response management. CSEE Journal of Power and Energy Systems. 2021;8(1):198-211.

[27] Azaroual M, Mbungu NT, Ouassaid M, Siti MW, Maaroufi M. Toward an intelligent community microgrid energy management system based on optimal control schemes. International Journal of Energy Research. 2022;46(15):21234-56.

[28] Lee ZE, Zhang KM. Regulated peer-to-peer energy markets for harnessing decentralized demand flexibility. Applied Energy. 2023;336:120672.

[29] Hossain MA, Pota HR, Squartini S, Zaman F, Muttaqi KM. Energy management of community microgrids considering degradation cost of battery. Journal of Energy Storage. 2019;22:257-69.

[30] Hossain MA, Chakrabortty RK, Ryan MJ, Pota HR. Energy management of community energy storage in grid-connected microgrid under uncertain real-time prices. Sustainable Cities and Society. 2021;66:102658.

[31] Rana MJ, Zaman F, Ray T, Sarker R. Real-time scheduling of community microgrid. Journal of Cleaner Production. 2021;286:125419.

[32] Guo J, Zhang P, Wu D, Liu Z, Liu X, Zhang S, et al. Multi-objective optimization design and multi-attribute decision-making method of a distributed energy system based on nearly zero-energy community load forecasting. Energy. 2022;239:122124.

[33] Sovacool BK, Dworkin MH. Global energy justice. Cambridge University Press; 2014.

[34] Lewis J, Hernández D, Geronimus AT. Energy efficiency as energy justice: addressing racial inequities through investments in people and places. Energy efficiency. 2020;13:419-32.

[35] Hernández D. Sacrifice along the energy continuum: a call for energy justice. Environmental Justice. 2015;8(4):151-6.

[36] Tarekegne B, Kazimierczuk K, O'Neil R. Communities in energy transition: exploring best practices and decision support tools to provide equitable outcomes. Discover Sustainability. 2022;3(1):12.

[37] Project EE. Energy Equity Framework: Combining data and qualitative approaches to ensure equity in the energy transition. University of Michigan – School for Environment and Sustainability (SEAS); 2022.

[38] Tarekegne B, Kazimierczuk K, O'Neil R. Advancing Energy Equity in Grid Planning. Pacific Northwest National Laboratory; 2022.

[39] Ademulegun OO, Flynn D, Hewitt NJ. Designing tariff for charging electric vehicles at home with equity in mind–The tripartite tariff. Sustainable Cities and Society. 2025;118:106018.

[40] Ashayeri M, Abbasabadi N. A framework for integrated energy and exposure to ambient pollution (iEnEx) assessment toward low-carbon, healthy, and equitable cities. Sustainable Cities and Society. 2022;78:103647.

[41] Tarekegne BW, Pennell GR, Preziuso DC, ONeil RS. Review of Energy Equity Metrics. Pacific Northwest National Laboratory; 2021.

[42] Molavi A, Shi J, Wu Y, Lim GJ. Enabling smart ports through the integration of microgrids: A two-stage stochastic programming approach. Applied Energy. 2020;258:114022.

7. Apendix

7.1. A.

The summary of the equity metrics discussed in section 2.3.2 are summarized in the Table 24.

Table 24: Overview of Equity Metrics

Metric	**Definition**
Program equity index	Assesses the distribution of program benefits across populations
Program accessibility	Evaluates the distribution of program eligibility across population groups
Energy cost index	Analyzes the distribution of energy cost across populations
Energy burden index	Details the distribution of energy burden across populations (e.g., 6% is considered high, 10% is severe)
Late payment index	Monitors the distribution of late bill payment habits across populations
Appliance performance	Measures access to energy efficiency measures
Household human development index	Tracks the distribution of HDI scores across population subgroups
Community acceptance rating	Gauges community satisfaction with investments
Program funding impact	Assesses the share of investment funds supporting disadvantaged communities
Energy use impacts	Evaluates the distribution of health and environmental impacts of energy investments
Workforce impact	Measures job creation and workforce development opportunities across populations
Program acceptance rate	Measures program enrollment percentages
Energy savings	Indicates energy use reductions in disadvantaged communities post implementation
Energy cost savings	Tracks reductions in energy costs
Change in energy burden	Assesses shifts in household energy expenses
Changes in HDI	Reflects overall socio-economic improvements in target communities

7.2. B.

Full output results that discussed in section 5.2 can be found in Tables 25-30.

Table 25: Cases 1-8 comparison of output variables for community 1

	Case 1	**Case 2**	**Case 3**	**Case 6**	**Case 4**	**Case 7**	**Case 5**	**Case 8**
Power Bought From the Grid (MWh)	0	127991.85	135323.82	135323.82	127991.85	127991.85	2612.89	127991.85
Power Sold to the Grid (MWh)	3229.67	0	0	0	0	0	1518.23	0
Load Shedding (MWh)	0	0	0	0	0	0	0	0
DER (MWh)	128390.29	0	0	0	0	0	124183.25	0
NonDER (MWh)	7185.29	7185.29	0	0	7185.29	7185.29	7185.29	7185.29
Charge (MWh)	17.1	576.02	576.02	576.02	576.02	576.02	305.18	576.02
Discharge (MWh)	9	630.02	630.02	630.02	630.02	630.02	330.1	630.02
Total Demand (MWh)	132354	132354	132354	132354	132354	132354	132354	132354
CESI	0.619	0.25	0.207	0.207	0.25	0.25	0.616	0.25
CEFI	0.888	0.525	0.5	0.5	0.525	0.525	0.883	0.525
CERI	0.598	0.587	0.587	0.587	0.587	0.587	0.597	0.587
Carbon Emission (lbs)	27335.58	53845.77	56935.44	56935.44	53845.77	53845.77	27527.16	53845.77

Table 26: Cases 9-16 comparison of output variables for community 1

	Case 9	**Case 10**	**Case 11**	**Case 14**	**Case 12**	**Case 15**	**Case 13**	**Case 16**
Power Bought From the Grid (MWh)	0	118055.06	135385.99	135385.99	135350.18	135350.18	107.09	118055.06
Power Sold to the Grid (MWh)	2224.08	0	0	0	0	0	3078.58	0
Load Shedding (MWh)	0	0	0	0	0	0	0	0
DER (MWh)	117653.88	0	0	0	0	0	118408.48	0
NonDER (MWh)	16933.2	16933.2	0	0	0	0	16933.2	16933.2
Charge (MWh)	18	746.75	1059.38	1059.38	746.75	746.75	59.38	746.75
Discharge (MWh)	27	826.73	1174.76	1174.76	826.73	826.73	72.98	826.73
Total Demand (MWh)	132354	132354	132354	132354	132354	132354	132354	132354
CESI	0.651	0.308	0.206	0.206	0.207	0.207	0.648	0.308
CEFI	0.894	0.559	0.5	0.5	0.5	0.5	0.903	0.559
CERI	0.794	0.784	0.587	0.587	0.782	0.782	0.793	0.784
Carbon Emission (lbs)	25049.69	49665.33	56961.83	56961.83	56946.61	56946.61	25255.28	49665.33

Table 27: Cases 1-8 comparison of output variables for community 2

	Case 1	**Case 2**	**Case 3**	**Case 6**	**Case 4**	**Case 7**	**Case 5**	**Case 8**
Power Bought From the Grid (MWh)	919.4	172722.51	191563.5	191563.5	181790.39	181790.39	14341.14	172722.51
Power Sold to the Grid (MWh)	1427.49	0	0	0	0	0	9.56	0
Load Shedding (MWh)	0	0	0	0	0	0	0	0
DER (MWh)	169501.12	0	0	0	0	0	154925.96	0
NonDER (MWh)	18461.07	18461.07	0	0	9577.32	9577.32	18461.07	18461.07
Charge (MWh)	1291.32	1568.93	1407.8	1407.8	1568.93	1568.93	1075.45	1568.93
Discharge (MWh)	1433.41	1733.25	1557.56	1557.56	1733.25	1733.25	1190.18	1733.25
Total Demand (MWh)	187286.4	187286.4	187286.4	187286.4	187286.4	187286.4	187286.4	187286.4
CESI	0.62	0.238	0.16	0.155	0.198	0.198	0.591	0.238
CEFI	0.87	0.545	0.5	0.5	0.519	0.519	0.825	0.545
CERI	0.64	0.628	0.58	0.581	0.628	0.628	0.637	0.628
Carbon Emission (lbs)	36472.81	72665.55	80597.55	80597.55	76485.57	76485.57	39015.46	72665.55
Power Cost ($)	80386.74	286691.8	315088.22	315088.22	302903.15	302903.15	110092.28	286691.8

Table 28: Cases 9-16 comparison of output variables for community 2

	Case 9	**Case 10**	**Case 11**	**Case 14**	**Case 12**	**Case 15**	**Case 13**	**Case 16**
Power Bought From the Grid (MWh)	0.17	139371.01	162047.7	162047.7	139343.38	139343.38	6736.8	139371.01
Power Sold to the Grid (MWh)	2955.38	0.04	0	0	0	0	1089.02	0.04
Load Shedding (MWh)	0	0	0	0	0	0	0	0
DER (MWh)	139323.48	0	0	0	0	0	130881.12	0
NonDER (MWh)	50955.18	50955.18	28731.96	28731.96	50955.18	50955.18	50955.18	50955.18
Charge (MWh)	27.15	27	0	0	0	0	228.51	27
Discharge (MWh)	64.21	54	0	0	0	0	275.11	54
Total Demand (MWh)	187286.4	187286.4	187286.4	187286.4	187286.4	187286.4	187286.4	187286.4
CESI	0.69	0.385	0.28	0.285	0.385	0.385	0.678	0.385
CEFI	0.91	0.624	0.56	0.558	0.624	0.624	0.881	0.624
CERI	0.92	0.907	0.49	0.491	0.492	0.492	0.775	0.907
Carbon Emission (lbs)	29663.43	58634.05	68178.41	68178.41	58622.42	58622.42	30697.76	58634.05
Power Cost ($)	57483.03	236571.7	278491.9	278491.9	236581.61	236581.61	74734.52	236571.7

Table 29: Cases 1-8 comparison of output variables for community 3

	Case 1	**Case 2**	**Case 3**	**Case 6**	**Case 4**	**Case 7**	**Case 5**	**Case 8**
Power Bought From the Grid (MWh)	351.78	100350.01	108582.18	108582.18	100350.01	100350.01	351.78	100350.01
Power Sold to the Grid (MWh)	2782.46	0	0	0	0	0	2782.46	0
Load Shedding (MWh)	0	0	0	0	0	0	0	0
DER (MWh)	100621.1	0	0	0	0	0	100621.1	0
NonDER (MWh)	15966.83	15966.83	7917.16	7917.16	15966.83	15966.83	15966.83	15966.83
Charge (MWh)	14.46	14.43	5.5	5.5	14.43	14.43	14.46	14.43
Discharge (MWh)	6.07	6.03	2.77	2.77	6.03	6.03	6.07	6.03
Total Demand (MWh)	114152.4	114152.4	114152.4	114152.4	114152.4	114152.4	114152.4	114152.4
CESI	0.663	0.34	0.286	0.286	0.34	0.34	0.663	0.34
CEFI	0.915	0.564	0.538	0.538	0.564	0.564	0.915	0.564
CERI	0.576	0.566	0.515	0.515	0.566	0.566	0.576	0.566
Carbon Emission (lbs)	21568.8	42216.18	45679.98	45679.98	42216.18	42216.18	21568.8	42216.18
Power Cost ($)	32530.11	167304.68	177506.6	177506.6	167304.68	167304.68	32530.11	167304.68

Table 30: Cases 9-16 comparison of output variables for community 3

	Case 9	**Case 10**	**Case 11**	**Case 14**	**Case 12**	**Case 15**	**Case 13**	**Case 16**
Power Bought From the Grid (MWh)	62.48	72620.46	91992.31	91992.31	72658.96	72658.96	62.48	72620.46
Power Sold to the Grid (MWh)	3362.71	14.71	5.3	5.3	16.6	16.6	3362.71	14.71
Load Shedding (MWh)	0	0	0	0	0	0	0	0
DER (MWh)	74441.5	0	0	0	0	0	74441.5	0
NonDER (MWh)	43180.63	43180.63	24149.01	24149.01	43180.63	43180.63	43180.63	43180.63
Charge (MWh)	1407.71	573.53	0	0	876.4	876.4	1407.71	573.53
Discharge (MWh)	1574.36	631.71	0	0	970.78	970.78	1574.36	631.71
Total Demand (MWh)	114152.4	114152.4	114152.4	114152.4	114152.4	114152.4	114152.4	114152.4
CESI	0.752	0.522	0.395	0.395	0.522	0.522	0.752	0.522
CEFI	0.949	0.673	0.58	0.58	0.673	0.673	0.949	0.673
CERI	0.728	0.721	0.491	0.491	0.645	0.645	0.728	0.721
Carbon Emission (lbs)	15874.98	30549.21	38703.74	38703.74	30565.58	30565.58	15874.98	30549.21
Power Cost ($)	19513.83	125613.13	161348.73	161348.73	125669.39	125669.39	19513.83	125613.13

7.3. C.

Full output figures that discussed in section 5.2 can be found in Figures 3-6.

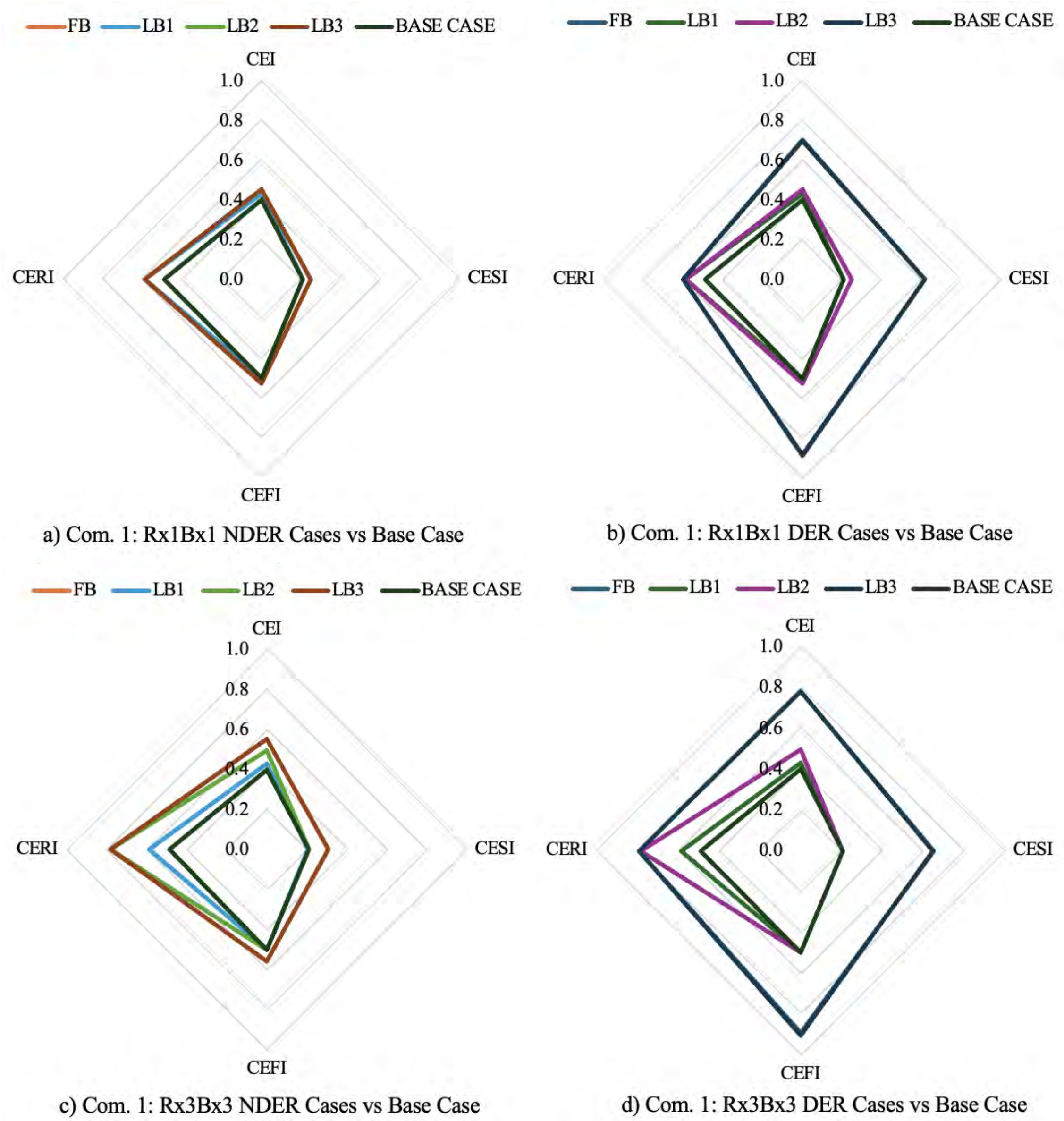
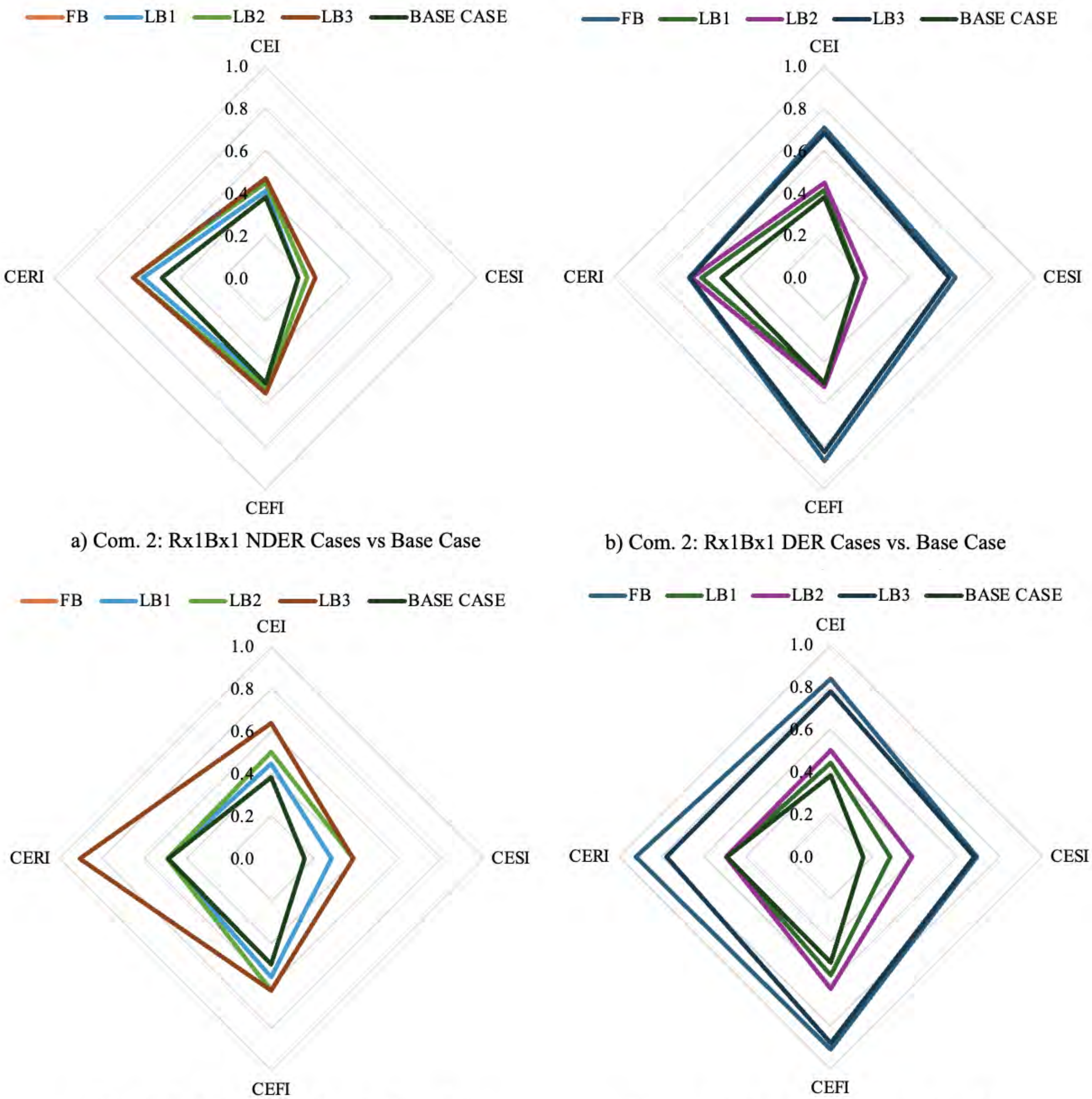


Figure 3: Community 1 equity index comparison under different budget scenarios. **a)** Without DER, renewable power source and energy storage capacity as planned. **b)** With DER, renewable power source and energy storage capacity as planned. **c)** Without DER, renewable power source and energy storage capacity expanded 3 times. **d)** With DER, renewable power source and energy storage capacity expanded 3 times.



a) Com. 2: Rx1Bx1 NDER Cases vs Base Case

b) Com. 2: Rx1Bx1 DER Cases vs. Base Case

c) Com. 2: Rx3Bx3 NDER Cases vs Base Case

d) Com 2: Rx3Bx3 DER Cases vs Base Case

Figure 4: Community 2 equity index comparison under different budget scenarios. **a)** Without DER, renewable power source and energy storage capacity as planned. **b)** With DER, renewable power source and energy storage capacity as planned. **c)** Without DER, renewable power source and energy storage capacity expanded 3 times. **d)** With DER, renewable power source and energy storage capacity expanded 3 times.

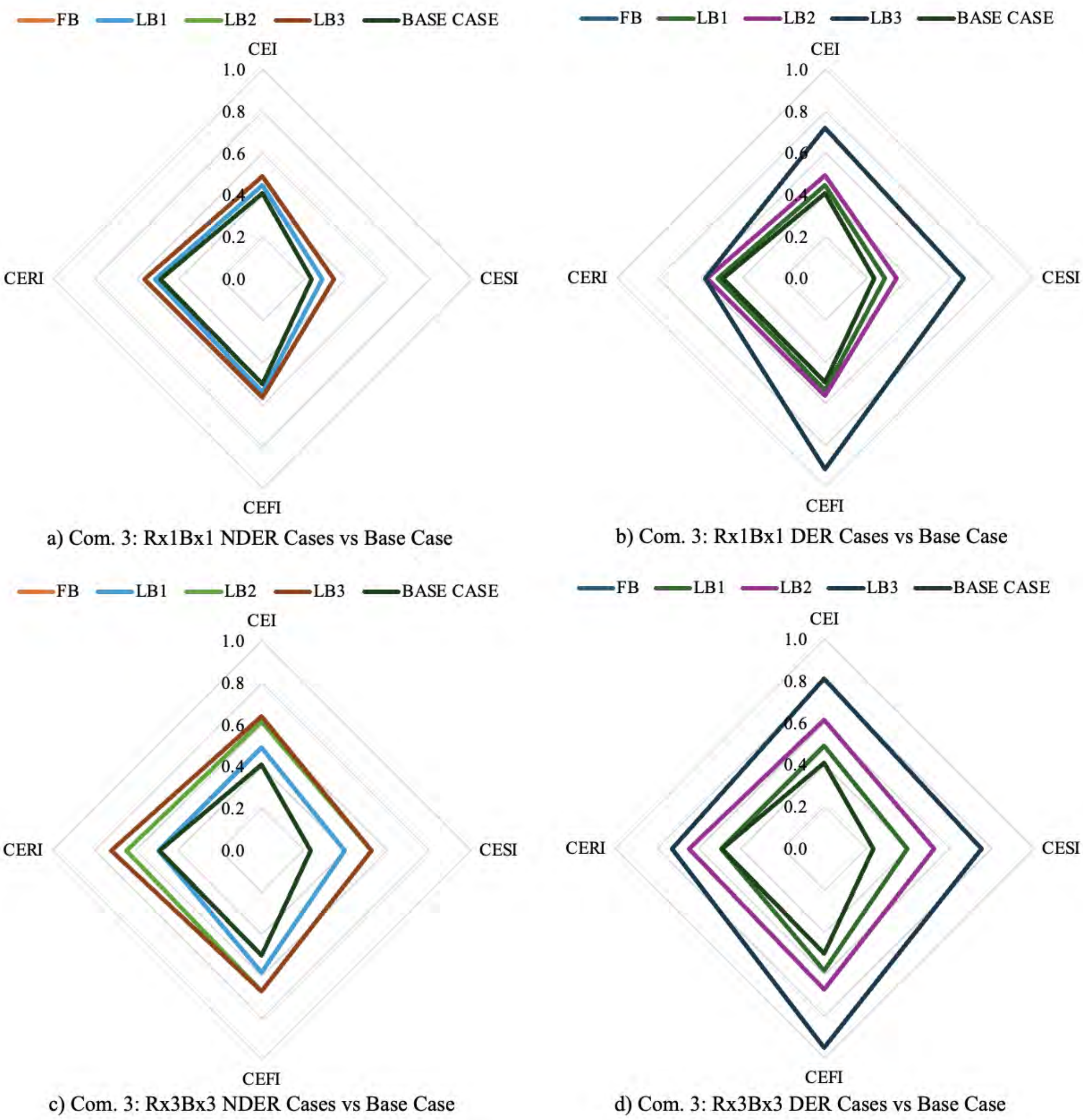
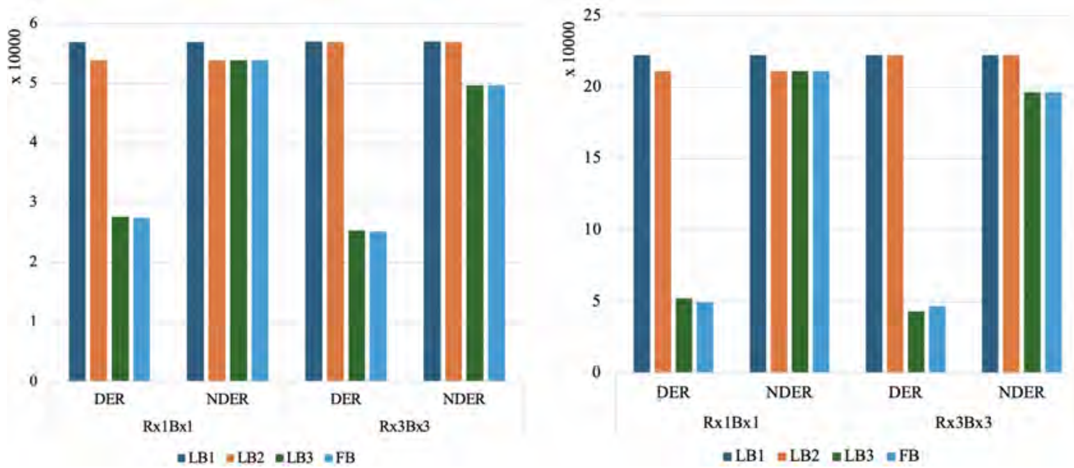
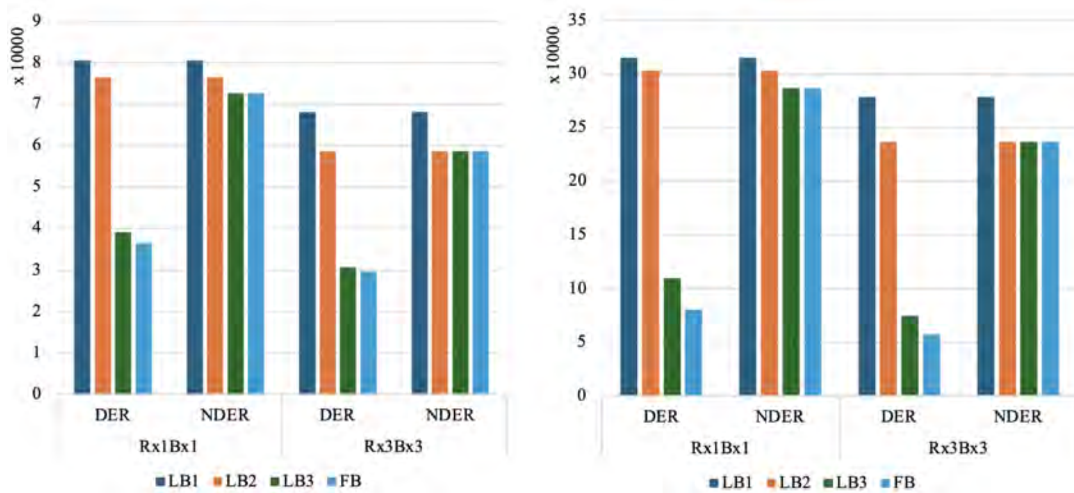


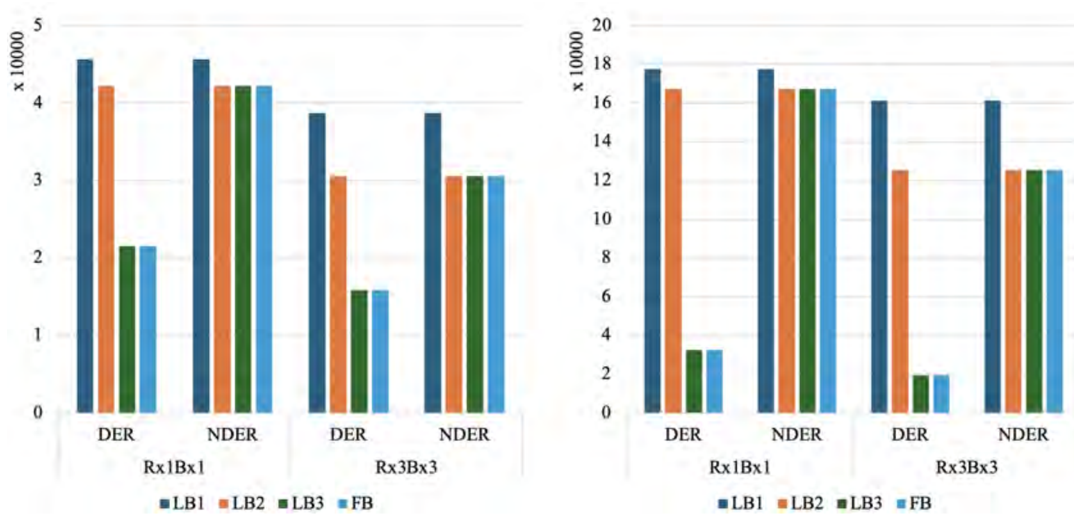
Figure 5: Community 3 equity index comparison under different budget scenarios. **a)** Without DER, renewable power source and energy storage capacity as planned. **b)** With DER, renewable power source and energy storage capacity as planned. **c)** Without DER, renewable power source and energy storage capacity expanded 3 times. **d)** With DER, renewable power source and energy storage capacity expanded 3 times.



(a) Community 1 Emission (left) and Power Cost (right) under various scenarios



(b) Community 2 Emission (left) and Power Cost (right) under various scenarios



(c) Community 3 Emission (left) and Power Cost (right) under various scenarios

Figure 6: Emission and Power Generation Cost comparison between different scenarios