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Toward equitable grid resilience: operationalizing climate adaptation strategies to mitigate flooding impacts

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Abstract

Disadvantaged communities are disproportionately affected by flooding, exacerbated by climate change. This paper presents a novel framework for incorporating environmental justice into climate adaptation planning of power grids against flooding. A new energy equity metric is introduced with the vision that addressing environmental justice warrants prioritizing disadvantaged communities that have lower risk thresholds. The framework is applied to a levee-protected IEEE standard test system in northern California. The grid performance disturbed due to flooded substations is investigated under current and future climate. The mathematical model of the framework is structured as a two-stage stochastic mixed-integer programming model. This model aims to minimize the equity gap in grid resilience (EGGR) between disadvantaged and non-disadvantaged communities while enhancing the system resilience by reducing the risk of power outages due to flooding. The results show that climate change undermines grid resilience, with disproportionally worse impacts on disadvantaged communities. A significant EGGR is observed that worsens under a changing climate. For adaptation, the optimal placement of distributed energy resources is determined by maximizing the grid resilience to flooding while minimizing EGGR. The proposed framework can equip decision-makers with a robust tool for operationalizing equitable climate adaptation strategies for power grids.

Notations and Abbreviations

Abbreviations

ac-OPF	AC optimal power flow
CalEPA	California Environmental Protection Agency
DAC	Disadvantaged community
DER	Distributed energy resources
DWR	Department of water resources
EUE	Expected unserved energy
EGGR	Equity gap in grid resilience
FEMA	Federal Emergency Management Agency
IEEE	Institute of electrical and electronics engineers
NLD	National levee database
OEHHA	Office of environmental health hazard assessment
RCP	Representative concentration pathway
SIMP	Stochastic mixed-integer programming

Parameters and Variables

B_g	DER placement budget
c_i^{ls}	Load shedding penalty cost function at bus i
f_i^P	Polynomial cost functions of active power injections at bus i
f_i^Q	Polynomial cost functions of reactive power injections at bus i
I_p	Grid resilience
$\boldsymbol{o}$	System operation decision variables
P_i^g	Active power injections at bus i
P_i^{ld}	Active load demand at bus i
P_i^{ls}	Active load shedding at bus i
$P(s)$	Probability of scenario s occurrence
Q_i^g	Reactive power injections at bus i
u_{ij}^s	A binary line damage variable; $u_{ij}^s = 1$ if line (i,j) is damaged under flooding scenario s, and 0 otherwise
u_i^s	A binary bus component damage variable; $u_i^s = 1$ if bus i is damaged under flooding scenario s, and 0 otherwise
w	Weighting factor
w_{max}	Maximum allowable weighting factor for load shedding penalty cost
x_i^g	A binary decision variable; $x_i^g = 1$ if a DER is placed at bus i, and 0 otherwise
x_i^w	A continuous decision variables indicating weighting factor for load shedding penalty cost at bus i
$\mathbb{E}_s\left[\frac{a}{b}\rho_D^0(u^s)\right]$	Expected ratio of delivered energy over energy demand in disadvantaged communities without DER placements
$\mathbb{E}_s\left[\frac{a}{b}\rho_{ND}^0(u^s)\right]$	Expected ratio of delivered energy over energy demand in non-disadvantaged communities without DER placements
$\mathbb{O}$	Feasible set of system operations
$\rho_D(u^s,x)$	Ratio of delivered energy over energy demand in disadvantaged communities given u^s and x
$\rho_{ND}(u^s,x)$	Ratio of delivered energy over energy demand in non-disadvantaged communities given u^s and x
$\rho_D^0(u^s)$	Ratio of delivered energy over energy demand in disadvantaged communities given u^s
$\rho_{ND}^0(u^s)$	Ratio of delivered energy over energy demand in non-disadvantaged communities given u^s
$\phi(u^s,x)$	EGGR with component damage variables u^s and planning decision variables x
$\mathbb{X}$	Set of feasible planning decisions
Ω_B	Set of buses in the system
Ω_D	Set of buses in disadvantaged communities
Ω_G	Set of generators in the system
Ω_{ND}	Set of buses in non-disadvantaged communities

1. Introduction

Several studies demonstrate that disadvantaged communities that already suffer from socioeconomic, health, and environmental barriers are more vulnerable to the adverse effects of extreme weather events and natural hazards worsened by climate change (West and Orr 2007, Karakoc *et al* 2020, Li *et al* 2020, 2022, Biniarz 2021, Ku *et al* 2021, Rendon *et al* 2021, Sanders *et al* 2022). For example, the nation's current average annual losses due to floods are over $32 billion in 2020's climate, which are borne disproportionately by disadvantaged communities (Wing *et al* 2022). The flood losses are projected to increase by over 26% by 2050 due to climate change, disproportionately impacting Black communities (Wing *et al* 2022). Environmental justice, as adopted by the (U.S. Department of Energy 2022), refers to 'the fair treatment and meaningful involvement of all people, regardless of race, color, national origin, or income, with respect to the development, implementation, and enforcement of environmental laws, regulations, and policies'. The recently passed $1.2T Infrastructure Investment and Jobs Act (Infrastructure law) (The White House 2022) primarily focuses on accelerating infrastructure adaptation to climate change and promoting environmental justice. The infrastructure law seeks to strengthen our aging infrastructure systems in several sectors while prioritizing disadvantaged communities. Further, the recent *Justice40* initiative (2022) (The White House 2021) obligates the U.S. federal government to allocate 40% of climate and clean energy investments into communities impacted by environmental injustice. Hence, an equitable infrastructure adaptation framework to the growing risk of extreme events and natural hazards is critically needed but still missing in the literature before the recent national infrastructure investments can achieve their goals in terms of resilience and environmental justice.

Energy plays a critical role in ensuring safety, economic prosperity, and well-being; thus, it needs to be a central pillar of any conversation for developing equitable climate adaptation strategies (Damavandi *et al* 2018, Nazemi *et al* 2020, Fournier *et al* 2022). The need is more pronounced when considering the effects of climate change, which is shown to worsen the patterns of extreme events. New patterns of extreme events can adversely affect the energy sector in different ways, including threatening the resilience of energy systems (e.g. by more severe flooding) and creating more energy demands (e.g. through worsening heatwaves and droughts). For example, over the last five years, the United States has experienced twice the number of power outages due to extreme weather events that it did in the early 2000s (United States Government Accountability Office 2021). Weather-related outages are estimated to be responsible for the U.S. economy losing \$25B to \$70B annually (The White House 2014). A lack of aggressive grid resilience enhancement strategies is estimated to lead to an increase in the costs of outages to utility customers by over \$480B in the 2080–2099 period (Larsen *et al* 2018, United States Government Accountability Office 2021). This issue is further elevated considering urbanization trends and land-use changes, which increase energy demands in urban areas and the interdependency among energy infrastructure and other infrastructure systems (Li *et al* 2022).

The objective of this study is to establish a framework for integrating environmental justice into optimal adaptation planning of power networks against flooding in a changing climate. The paper introduces a new metric, EGGR, to encapsulate the risk of power outages due to extreme events (flooding in this study) in a changing climate among different communities. This metric is built upon the concept of 'equitable risk' and is presented in a form comparable to fragility curves while recognizing that disadvantaged communities have lower levels of risk tolerance and adaptive capacity. In the next step, we present a two-stage SIMP model to determine optimal adaptation strategies for power grids that maximize the grid resilience to flooding while minimizing the equity gap between disadvantaged and non-disadvantaged communities. For demonstration, the proposed framework is applied to a modified IEEE 30-bus standard test system placed on a levee-protected area in Central Valley, northern California. The performance of the power network disturbed due to flooded substations is examined under current and future climate scenarios for disadvantaged and non-disadvantaged communities within the study area. For adaptation, the optimal placement of DER is determined by formulating an optimization problem with the objective function of maximizing the network resilience to flooding while minimizing EGGR.

2. Background: energy justice and equity

Energy justice is an emerging concept that has gained significant attention in the literature and policy discussions (e.g. Sovacool and Dworki 2015, Jenkins *et al* 2016, Reames 2016, Bednar and Reames 2020, Heffron 2022, Bouzarovski *et al* 2023). Pursuing energy equity and justice poses a multi-dimensional and transdisciplinary endeavor that needs to be seamlessly addressed across energy domains, such as clean energy, affordable energy, resilient energy systems (e.g. power networks), energy-efficient housing and transportation, among others (e.g. He *et al* 2018, Trudeau 2018, Ucal *et al* 2020, Bouzarovski *et al* 2023). As per the Washington Clean Energy Transformation Act (2019) (Energy and Act 2019), the public interest includes 'The equitable distribution of energy benefits and reduction of burdens to vulnerable populations and highly impacted communities; long-term and short-term public health, economic, and environmental benefits and the reduction of costs and risks; and energy security and resiliency'. For instance, disadvantaged communities are shown to have historically been burdened by underinvestment in clean energy infrastructure and access to energy-efficient transportation and housing (O'neil *et al* 2021).

As noted previously, equity can be investigated in various energy domains, such as affordable and clean energy, resilient energy systems, and energy-efficient housing. This study focuses on energy equity pertinent to resilient power systems against extreme climatic events in a changing climate. While several studies are performed to study energy equity and justice across different domains, limited work is performed to examine energy equity in terms of resilient power systems against extreme climatic events (e.g. floods) in a changing climate. Several studies have demonstrated that historically underserved and socially vulnerably communities are more vulnerable and exposed to flood risk, primarily due to socioeconomic and environmental barriers, marginal infrastructure, and lack of awareness and resources, among others (e.g. Burton and Cutter 2008, Sanders *et al* 2022, Wing *et al* 2022, Vahedifard *et al* 2023). Ensuring that vulnerable communities have reliable access to energy during and after natural extreme climatic events (e.g. floods) is a crucial element of energy justice. Resilience planning includes efforts to protect these communities during emergencies.

The rapidly growing interest and demands for promoting equitable adaptation strategies have motivated utility companies to develop climate adaptation vulnerability assessments while considering community engagement plans (e.g. Public Utilities Commission of the State of California Energy Division 2021, Southern California Edison Company's 2022). Toward energy equity, it is necessary to design and develop technologies, procedures, regulations, and policies that facilitate an equitable distribution of benefits in the energy system (O'neil *et al* 2021). However, gaps remain in the literature regarding a comprehensive yet practical framework that empowers decision-makers and stakeholders to develop adaptation strategies for climate-resilient energy systems embracing equity considerations.

3. New energy equity metric for resilient power grids

A critical prerequisite for developing equitable energy adaptation strategies is to define a reliable and comprehensive metric that can be used for analysis and modeling purposes. Such a metric is required to provide a basis for quantifying the energy disparity among communities. Climate adaptation and resilience enhancement strategies must be developed with the vision of eliminating this disparity under current and future climates. While limited attempts have been made to define metrics in terms of affordable energy (e.g. Cong *et al* 2022), to the best of the authors' knowledge, there is no metric in the literature to address the equity for a resilient power grid in the face flooding exacerbated by climate change. This study proposes EGGR as a new energy equity metric to encapsulate the risk of power outages due to extreme events (flooding in this study) in a changing climate among different communities. The proposed EGGR is motivated by the vision that fulfilling environmental justice and equity criteria requires further improvements to lower the risk of power outages in disadvantaged communities. This vision is based on the well-known fact that disadvantaged communities are disproportionately impacted by extreme events and are at greater risk of experiencing negative impacts related to natural hazards and extreme events.

Figure 1(a) schematically shows the risk of power outages due to flooding for disadvantaged and non-disadvantaged communities before and after a desirable adaptation. Figure 1(b) schematically depicts the proposed metric. This metric is built upon the concept of 'equitable risk' and is presented in a form comparable to fragility curves while recognizing that disadvantaged communities have lower levels of risk tolerance and adaptive capacity. Thus, the risk posed to disadvantaged communities is weighted to account for their lower risk tolerance and adaptive capacity. Per definition (e.g. Kennedy *et al* 1980, Baker 2015), a fragility curve establishes the relationship between the probability of failure of a system for given extreme loading conditions (e.g. earthquake, flooding). Fragility curves are proven to provide robust and practical tools for risk assessment purposes and are extensively used for different infrastructure systems in the literature (Schultz *et al* 2010, Jasim *et al* 2017, Vahedifard *et al* 2020, Darestani *et al* 2021, Dehghani *et al* 2022).

As shown in figure 1(b), the x-axis of the proposed metric represents the probability of flooding, which is the primary factor disturbing the performance of the power grid by reducing the delivered energy to customers. This probability of flooding can increase due to climate change. Previous studies show that climate change worsens the intensity and frequency of extreme precipitation and floods in several regions (Ragno *et al* 2018, Chen *et al* 2019, Mallakpour *et al* 2020). For example, due to climate change, future extreme precipitation events, compared to historical events, may become 20% more intense and twice as frequent in highly populated areas across the United States. The flood frequency is inversely proportional to the probability of flooding. A flood with a 100 year return period represents a probability of flooding of 0.01 under the assumption of stationarity (Raed and Vogel 2015). If the flood presently associated with a 100 year return period becomes a 50 year event due to climate change, the probability of flooding increases from 0.01 to 0.02. For a levee-protected area in northern California, the probability of flooding is projected to increase from 0.01 up to 0.069 under a RCP of 8.5 (Miraee-Ashtiani *et al* 2022). Changes in the probability of flooding over a study area alter the probability of failure at the component and, subsequently, at the system level of a power network. Previous studies show that substations are the most vulnerable components of power grids to flooding (Boggess *et al* 2014, Amicarelli *et al* 2020, Movahednia *et al* 2022).

The y-axis of the proposed metric, in figure 1(b), is defined as the ratio of 'delivered energy' to 'energy demand'. This ratio aims to quantify the power outage risk for a given flood probability at the component (substation) or system level. In this study, the system-level ratio is used in the analyses. The first step is establishing the curves of power outage risks for disadvantaged and non-disadvantaged communities before considering any adaptation measures. This allows quantifying the *EGGR*. The *EGGR* is graphically depicted as the difference between the curves of power outage risks for disadvantaged and non-disadvantaged communities. Disadvantaged communities are prioritized for adaptation planning purposes to account for their lower risk tolerance and adaptive capacity. This prioritization is performed by assigning a 'weight' to the cost of the curtailed load of disadvantaged communities in the calculations shown on the y-axis. The magnitude of this weight is determined through an optimization process with the goal of minimizing the *EGGR* after the adaptation. If no *EGGR* is determined in the preadaptation analysis, this weight will be equal to unity. As shown in figure 1, the goal of adaptation is to reduce the risk of power outage in each community

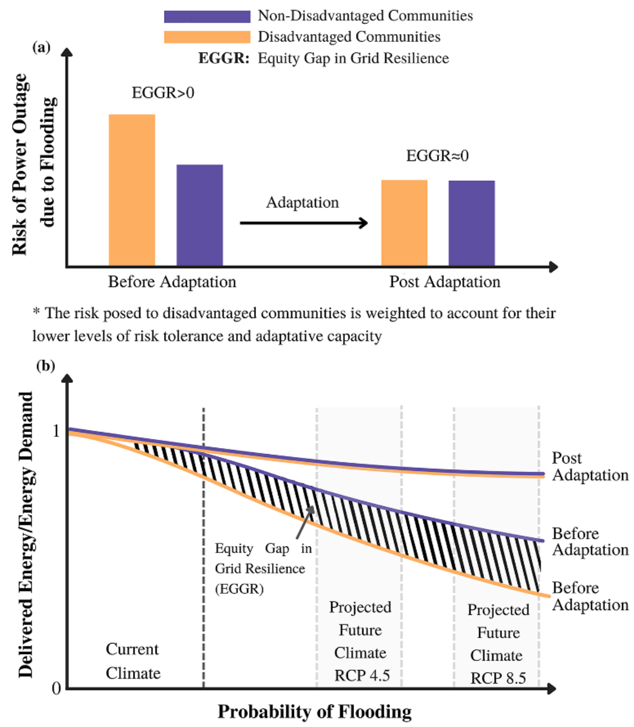

Figure 1. Proposed energy equity metric based on the ratio of delivered energy to demanded energy vs. flood probability for pre- and post-adaptation scenarios.

by matching and enhancing the curves representing the power outage risks for disadvantaged and non-disadvantaged communities after the adaptation.

4. Study system

Figure 2 depicts the study system, which involves a modified IEEE 30-bus standard test system overlaid on a levee-protected area in Central Valley, northern California. Due to rapid urbanization and land-use changes, the power grid is becoming increasingly interdependent with other infrastructure systems (Foster 2001, Hasan *et al* 2015, Chuan *et al* 2018). The power grid in many regions is protected from flooding by levees. In the United States, two-thirds of the population live in counties with at least one earthen levee (ASCE 2021). The average age of the nation's levees is about 50 years, with many operating under marginal or below-average conditions and the possibility of breaching 80% of high-risk levees before they overtop (Vahedifard *et al* 2016, ASCE 2021). The impacts of climate change on the frequency and intensity of flood events can adversely affect the vulnerability of levee systems (Mallakpour *et al* 2020, Ucal and Xydis 2020), and, subsequently, levee-protected communities and infrastructure systems such as power systems (Vahedifard *et al* 2016, Panteli *et al* 2017, Darestani *et al* 2019). A recent study (Vahedifard *et al* 2023) shows that disadvantaged communities are overrepresented behind levees compared to non-leveed areas in several regions across the United States, including California.

4.1. Flood hazards in a changing climate

California, the nation's most populous state, has more than 15 000 km of levees protecting land and infrastructure from floods. Previous studies suggest that a warming climate worsens flood hazards in California (Hamlet *et al* 2007, AghaKouchak *et al* 2014, Osaka *et al* 2020, Wasko *et al* 2020). It is estimated that California's levee system will face substantial increases in flood hazards in the future, mainly due to climate change (Mallakpour *et al* 2020). The selected study area contains six levee systems (figure 2).

The National Levee Database (NLD 2022) is used to determine the locations of these levee systems and their protected areas. As shown in table 1, each levee system is identified with an ID system. In this study, these six levee systems are numbered from 1 to 6. Based on a predicted return period of 100 years, RP_{future}, table 1 summarizes the projected further flood return period and probability of the historically 100 year flood for each of the six levee systems for RCP 4.5 (representing a moderate emissions scenario) and RCP 8.5 (representing a business as usual emissions scenario). RCPs represent possible future scenarios for

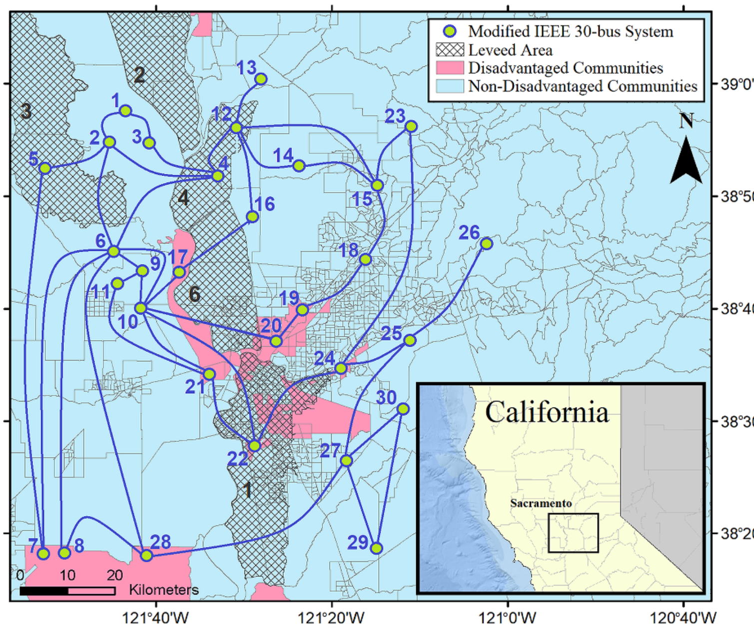

Figure 2. Study area: maps of power system and disadvantaged communities overlaid on levee-protected regions in Northern California.

Table 1. Return period & projected future probability of 100-year floods for Levee systems in the study area.

		RP_{future} (yrs)		P_{flood}	
Region no.	Levee system ID	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5
1	5205000441	35.2	21.6	0.028	0.046
2	5205000521	35.5	17.6	0.028	0.057
3	5205000561	31.0	16.5	0.032	0.061
4	5205000922	26.0	14.5	0.038	0.069
5	5205001151	40.9	21.2	0.024	0.047
6	5205000923	49.6	59.9	0.020	0.017
RP_{future}	Future return period of a flood currently known as 100 year flood				
P_{flood}	Future probability of a flood currently known as 100 year flood				

greenhouse gas and aerosol emissions. RCP scenarios are defined by total solar radiative forcing by 2100. RCP 4.5 represents a moderate scenario in which emissions reach a peak point around the year 2040 and then decline. On the other hand, RCP 8.5 represents the highest baseline emissions scenario in which emissions constantly increase throughout the twenty-first century. In this study, we assumed a flood currently associated with a 100 year return period could trigger a failure in a substation in the study area. Then, the change in the return period of the currently known 100 year flood due to changing climate is calculated. We used the results reported by (Miraee-Ashtiani *et al* 2022) to determine the projected future flood return period and probability of the historically 100 year flood for each of the six levee systems for RCP 4.5 and RCP 8.5 (table 1). For completeness, the methodology used by (Miraee-Ashtiani *et al* 2022) is summarized in the rest of this section.

We employed 1950–2005 as the historical period and 2020–2099 as the future period. We used gridded simulated daily runoff from four global circulation models (GCMs) provided by the Fifth Coupled Model Inter-comparison Project (CMIP5) to examine the evolution in the flood probability under different future climate scenarios (RCP 4.5 and 8.5). The four GCMs used in this study are recommended by the 4th California Climate Change Assessment and include: CNRM-CM5 (representing cool/wet condition), HadGEM2-ES (representing warm/dry condition), MIROC5 (representing complement climate condition), and CanESM2 (representing average climate condition). The daily gridded total runoff used here is developed at the Scripps Institution of Oceanography, University of California, San Diego. In the next step, using the gridded daily runoff, the maximum daily runoff per year for each climate model and emission scenario is determined using the annual block maximum sampling method. The annual maximum daily runoffs are then fit to a generalized extreme value distribution to estimate the flood frequency distribution for each pixel of the study area for the historical and future periods. The extreme value theory is utilized to determine the projected future return period of the historically 100 year flood (i.e. 1% probability of occurrence based on the historical data). The values are used to determine the changes in the flood return period for each pixel for each climate model and each RCP. The last step involves the spatial averaging of the future return period, RP_{future}, corresponding to the historically 100 year flood ($RP_{\text{hist}} = 100$ years) for each leveed area. For each leveed area, the probability of flooding is the inverse of the corresponding return period.

As shown in table 1, the levee system ID 5205000922 (Region 4) represents the highest level of change among the six levee systems, where a flood associated with the current 100 year return period will have a projected future return period of 26.0 and 14.5 years, respectively, under RCP 4.5 and 8.5. The minimum change is observed in levee system ID 5205000923 (Region 6), in which a flood currently associated with a 100 year return period is projected to occur every 49.6 and 59.9 years in the future under RCP 4.5 and RCP 8.5, respectively.

4.2. Identification of disadvantaged communities

Disadvantaged communities in the study area (figure 2) are identified through the designation of California's disadvantaged communities defined by the CalEPA, recently updated in May 2022 (California Office of Environmental Health Hazard Assessment 2022). The designation is made based on the scores determined by the new version of the California Communities Environmental Health Screening Tool: CalEnviroScreen 4.0 (California Office of Environmental Health Hazard Assessment 2022). CalEnviroScreen, developed by the California OEHHA (CalEnviroScreen 4.0 2021), provides a screening tool to identify California communities disproportionately affected by multiple sources of pollution. CalEnviroScreen assigns a numerical score for each census tract in California by using environmental, health, and socioeconomic information. In the new designation, CalEPA defines four categories of geographic areas as disadvantaged (California Office of Environmental Health Hazard Assessment 2022):

- Census tracts received the highest 25% overall scores in CalEnviroScreen 4.0.
- Census tracts that lack overall scores in CalEnviroScreen 4.0 due to data gaps but received the highest 5% of CalEnviroScreen 4.0 cumulative pollution burden scores.
- Census tracts identified in the 2017 DAC designation as disadvantaged, regardless of their scores in CalEnviroScreen 4.0. The 2017 DAC designation was defined by the California DWR as census geographies with an annual median household income (MHI) of less than 80% of the statewide yearly MHI (California Department of Water Resources 2022).
- Land under the control of federally recognized Tribes.

It is noted that the proposed methodology can be used in conjunction with other related tools and indices, such as the climate and economic justice screening tool (CEQ 2022), to identify disadvantaged communities.

4.3. Power network system

As shown in figure 2, a modified IEEE 30-bus standard test system is overlaid spatially on the study area. The IEEE 30-bus standard test system approximates the American Electric Power system as it existed in December 1961 (Dabbagchi *et al* 1993). The system has 30 buses, 6 generators, 20 loads, and 41 transmission lines, with a total real power demand of 189.2 MW. The network data are obtained from the source code package of MATPOWER v7.1 (Dabbagchi and Christie 1993, Zimmerman *et al* 2022). Overlaying the test power network system on the levee-protected area and the disadvantaged communities' map enables the identification of the flooded buses (substations) and the substations falling in the disadvantaged communities. The tributary area of a substation falling in a DAC may also include non-disadvantaged communities and vice versa. However, for simplicity, this study assumes the tributary area of each substation is limited to the community in which the substation geographically falls. Moreover, this study assumes that a flood currently associated with a 100 year return period triggers a failure in the substations in the study area. That is, under the current climate, the probability of failure of inundated substations is 0.01. The 100 year flood is considered the minimum flood protection level by the FEMA and the U.S. National Flood Insurance Program (NFIP) (FEMA 2005). For projected future climate scenarios, the projected future probability of flooding of the currently known 100 year flood is considered as the probability of failure of inundated substations. For instance, the projected future probability of failure of inundated substations falling in Region 6 is 0.020 and 0.017 for RCP 4.5 and RCP 8.5, respectively.

5. Methodological framework

Figure 3 shows the flowchart of the proposed framework. The main goal of the framework is to delineate the optimal adaptation strategies (here, the DER location and weighting factor, W) to minimize the risk of

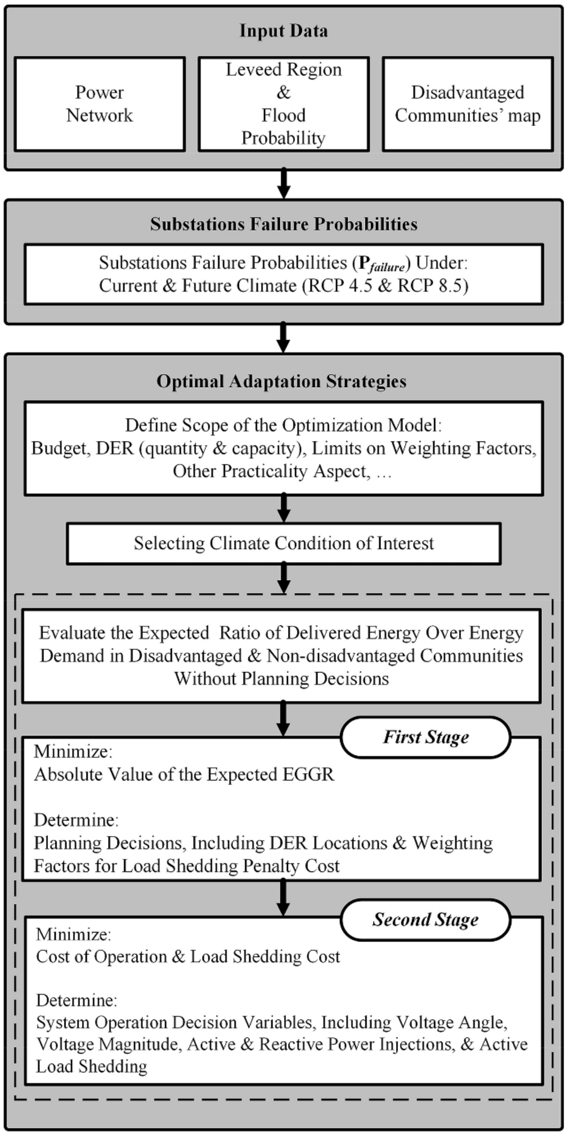

Figure 3. The flowchart depicting the optimization process.

flood-induced power outages in a changing climate while prioritizing disadvantaged communities. A comprehensive flood risk assessment warrants investigating the three components of hazard, exposure, and vulnerability (USACE 2018). This study considers all three components in the calculations through (i) using the probability of flooding under current and projected future (i.e. hazard level), (ii) identifying the inundated substations and communities (i.e. exposure), and (iii) determining the EUE due to flooding (i.e. vulnerability).

5.1. Input data

As depicted in figure 3, the first step involves defining the input data, including the power network data, the map of the leveed-protected regions with the associated flood probability for each region under current and future climate scenarios, and the map of disadvantaged communities. Overlaying these input layers leads to identifying the probability of failure of substations due to flooding and the tributary area of each substation, including whether or not the substation serves disadvantaged communities.

5.2. Adaptation strategies

In the next step, the scope of the optimization model is defined. For example, acceptable ranges for weighting factors as well as the DER capacity and numbers are defined, e.g. based on an allocated budget, practical considerations, etc. It is noted that other adaptation measures can be considered in the optimization process. However, in this study, only the DER location is sought through optimization. After forming the scope of the optimization model, the climate condition of interest is selected. For this climate condition, the ratio of expected 'delivered energy' to expected 'energy demand' for disadvantaged and non-disadvantaged communities is evaluated before adaptation (figure 1(b)). This serves as an index for power grid resilience (I_ρ) with an ideal value being at unity. Subsequently, the optimization model is solved for the given climate condition to reach optimal adaptation strategies. The objective of the first stage is to minimize the absolute value of *EGGR*, which is the difference between the ratio of expected delivered energy to the expected energy demand of disadvantaged and non-disadvantaged communities for a given flood probability (figure 1(b)). The ac-OPF and load shedding methods (Thurner *et al* 2018, Koenig *et al* 2020, Darestani *et al* 2022) are used to represent the second stage of the model. This process is repeated for current and future climate scenarios. For climate adaptation, the optimal DER placement obtained for the projected future flood hazard levels is incorporated.

5.3. Mathematical model of optimization

The mathematical model of the presented framework is structured as a two-stage SMIP model. This model aims to minimize the gap in the risk of power outages among disadvantaged and non-disadvantaged communities measured through *EGGR* while enhancing the system's resilience to flooding. The planning decisions include DER placement and weighting factor (W), which applies to curtailed load cost. The SMIP model's second stage evaluates the system operation cost under a flooding scenario. This stage is an ac-OPF problem that aims to minimize the cost of power injections and load shedding penalty cost given a flooding scenario by determining optimal system operation variables. The general form of the SMIP model is

$$\min_{\boldsymbol{x}\in\mathbb{X}} \left|\mathbb{E}_s\left[\frac{a}{b}\phi\left(\boldsymbol{u}^s,\boldsymbol{x}\right)\right]\right| \tag{1}$$

where $\boldsymbol{u}^s$ and $\boldsymbol{x}$ indicate binary component damage variables under flooding scenario s and mixed-integer planning decision variables, respectively. In this model, $u^s_{ij} = 1$ if line (i,j) is damaged in scenario s, and 0 otherwise. With a similar analogy, $u^s_i = 1$ if bus i is damaged in scenario s, and 0 otherwise. The planning decision variables consist of binary decision variables for DER placement, $\boldsymbol{x}^g$, and continuous decision variables indicating weighting factors for load shedding penalty cost, $\boldsymbol{x}^w$. In this model, the objective is to minimize the absolute value of the expected *EGGR* that is

$$\mathbb{E}_s\left[\frac{a}{b}\phi\left(\boldsymbol{u}^s,\boldsymbol{x}\right)\right] = \sum_{s\in\mathcal{S}} P(s)\,\phi\left(\boldsymbol{u}^s,\boldsymbol{x}\right) \tag{2}$$

where $P(s)$ is defined as the probability that scenario s occurs, $\phi\left(\boldsymbol{u}^s,\boldsymbol{x}\right)$ represents *EGGR* with component damage variables, $\boldsymbol{u}^s$, and planning decision variables, $\boldsymbol{x}$, which is defined as

$$\phi\left(\boldsymbol{u}^s,\boldsymbol{x}\right) = \rho_{ND}\left(\boldsymbol{u}^s,\boldsymbol{x}\right) - \rho_D\left(\boldsymbol{u}^s,\boldsymbol{x}\right) \tag{3}$$

where $\rho_D\left(\boldsymbol{u}^s,\boldsymbol{x}\right)$ and $\rho_{ND}\left(\boldsymbol{u}^s,\boldsymbol{x}\right)$ denote the ratio of delivered energy over energy demand in disadvantaged and non-disadvantaged communities, given $\boldsymbol{u}^s$ and $\boldsymbol{x}$, respectively. In the SMIP model (1), $\mathbb{X}$ denotes the set of feasible planning decisions defined as

$$\mathbb{X} = \left\{\sum_{n=0}^{N} xx \sum_{n} x \,\middle|\, \sum_{i\in\Omega_B} x^g_i \leqslant B_g \right. \tag{4}$$

$$x^g_i \in \{0,1\},\ \forall i\in\Omega_B \tag{5}$$

$$x^w_i \in \left[1, w_{max}\right],\ \forall i\in\Omega_B \tag{6}$$

$$\mathbb{E}_s\left[\rho_D\left(\boldsymbol{u}^s,\boldsymbol{x}\right)\right] \geqslant \mathbb{E}_s\left[\rho^0_D\left(\boldsymbol{u}^s\right)\right] \tag{7}$$

$$\left.\mathbb{E}_s\left[\rho_{ND}\left(\boldsymbol{u}^s,\boldsymbol{x}\right)\right] \geqslant \mathbb{E}_s\left[\rho^0_{ND}\left(\boldsymbol{u}^s\right)\right]\right\} \tag{8}$$

where x^g_i indicates whether a DER is placed at bus i or not, x^w_i presents the weighting factor for load shedding penalty cost at bus i, Ω_B indicates the set of buses in the system, B_g is DER placement budget, which is defined as the maximum number of DERs that can be placed in the system, $w_{\max}$ denotes the maximum allowable weighting factor for load shedding penalty cost, and $\rho^0_D\left(\boldsymbol{u}^s\right)$ and $\rho^0_{ND}\left(\boldsymbol{u}^s\right)$ denote the ratio of delivered energy over energy demand in disadvantaged and non-disadvantaged communities given $\boldsymbol{u}^s$, respectively. Therefore, $\mathbb{E}_s\left[\rho^0_D\left(\boldsymbol{u}^s\right)\right]$ and $\mathbb{E}_s\left[\rho^0_{ND}\left(\boldsymbol{u}^s\right)\right]$ are the expected ratio of delivered energy over energy demand in disadvantaged and non-disadvantaged communities when no planning decisions of DER placements are applied to the system. These expected ratios can be computed for the system prior to solving the SMIP model. Constraint (4) limits the total number of DERs. Constraints (5) indicate possible decisions regarding DER placements, where $x^g_i = 1$ if a DER is placed at bus i, and 0 otherwise. Constraint (6) sets the limits on weighting factors for load shedding penalty costs at buses. Constraints (7) and (8) impose limits on the expected ratio of delivered energy over energy demand in disadvantaged and non-disadvantaged communities, respectively. These two constraints are defined to ensure maintaining and enhancing the system resilience in both disadvantaged and non-disadvantaged communities.

For a given scenario and planning decision variables (*i.e.* known $\boldsymbol{u}^s$ and $\boldsymbol{x}$), the delivered energy in disadvantaged and non-disadvantaged communities can be obtained after solving the ac-OPF model given by

$$\min_{O\in\mathbb{O}(\boldsymbol{u}^s,\boldsymbol{x})} \left\{ \sum_{i\in\Omega_B} c_i^{ls}\left(x_i^w, P_i^{ls}\right) + \sum_{i\in\Omega_G} \left[f_i^P\left(P_i^g\right) + f_i^Q\left(Q_i^g\right) \right] \right\} \tag{9}$$

where $\boldsymbol{o}$ and $\mathbb{O}$ indicate system operation decision variables and feasible set of system operations, respectively. In this model, system operation variables include voltage angle, voltage magnitude, active and reactive power injections, and active load shedding in the system. The feasible set of system operations refers to the conservation of flow and capacity constraints in the ac-OPF problem, and c_i^{ls} denotes the load shedding penalty cost function at bus i, which is defined as a function of weighting factors for load shedding penalty cost at that bus (*i.e.* x_i^w) and active load shedding at bus i (*i.e.* P_i^{ls}). Also, f_i^P and f_i^Q represent the polynomial cost functions of active and reactive power injections (P_i^g and Q_i^g) at bus i, respectively.

When the ac-OPF problem is solved for a given $\boldsymbol{u}^s$ and $\boldsymbol{x}$, the optimal system operation decision variables, including active load shedding, are determined. Then, $\rho_D\left(\boldsymbol{u}^s,\boldsymbol{x}\right)$ and $\rho_{ND}\left(\boldsymbol{u}^s,\boldsymbol{x}\right)$ are calculated from

$$\rho_D\left(\boldsymbol{u}^s,\boldsymbol{x}\right) = 1 - \frac{\sum_{i\in\Omega_D} P_i^{ls}}{\sum_{i\in\Omega_D} P_i^{ld}} \tag{10}$$

$$\rho_{ND}\left(\boldsymbol{u}^s,\boldsymbol{x}\right) = 1 - \frac{\sum_{i\in\Omega_{ND}} P_i^{ls}}{\sum_{i\in\Omega_{ND}} P_i^{ld}} \tag{11}$$

where Ω_D and Ω_{ND} denote the set of buses in disadvantaged and non-disadvantaged communities, respectively, and P_i^{ld} indicates the active load demand at bus i.

6. Results

The proposed approach is applied to quantify the impact of flooding on the tested power grid (i.e. modified IEEE 30-bus standard test system) for disadvantaged communities, non-disadvantaged communities, and the entire power grid across the study area. The results are presented under different climate conditions and adaptation scenarios. For each climate condition and adaptation scenario, the EUE is determined separately for disadvantaged and non-disadvantaged communities to characterize disparity in terms of flood-induced power outages. The current climate represents a flood probability of 1% (i.e. floods with a return period of 100 years). Projected future climate conditions are considered under RCP 4.5 and RCP 8.5. For adaptation purposes, the number of DERs is limited to 3, which are placed on each bus individually, and are not placed on any flooded buses. Three cases are examined, each representing a DER power capacity: 2 MW for Case I, 3 MW for Case II, and 5 MW for case III. Hence, a maximum of 15 MW is considered, representing a reasonable level of 7.9% of the overall load of 189.2 MW in the IEEE 30-bus standard test system. The preadaptation grid is considered the baseline for comparison. In the optimization process, the weighting factor (W) for disadvantaged communities varied from 1.0 to 1.006, with an increment of 0.001. Beyond 1.006, no improvement is observed.

Table 2 presents the optimal results, which are those leading to the lowest EGGR. The results for four weighting factors of $W = 1$, 1.002, 1.004, and 1.006 are shown in figures 4–7, respectively. Two ways of showing the same results are used: the top figure uses light-colored (wide) bars for non-disadvantaged communities and dark-colored (narrow) bars for disadvantaged communities, and the bottom figure uses solid lines for preadaptation and dashed lines for post-adaptation (for three cases). The best planning strategy resulting from this optimization provides a weighting factor equal to $W = 1.006$, and 5 MW capacity for each DER (i.e. Case III). However, the best location of DERs depends on which climate condition is chosen. Buses 2, 12, and 20 are the best locations for installing DER for project future climate RCP 8.5. However, buses 2, 18, and 11 are the best locations for current climate conditions. If RCP 4.5 is chosen as the projected future climate scenario, the best DER locations will be buses 7 and 18, meaning that adding over 10 MW DER will not decrease the EGGR.

Figures 4–7 illustrate how the proposed concept of energy equity in figure 1. can be achieved through adaptation planning while enhancing the grid resilience against flooding. The results can be used to delineate the effect of climate change on grid resilience, disparity (EGGR) in pre- and post-adaptation, and possible improvements made through an optimal DER placement while integrating environmental justice

Table 2. The optimal DER location and weighting factor for 0, 2, 3, and 5 MW of DER capacity under current and future climate conditions, when flooded buses are [4, 5, 12, 22].

Climate condition		Optimal DER location	Optimal weighting factor	$(I_\rho)\,\mathbb{E}_s[\rho_D]$	$(I_\rho)\,\mathbb{E}_s[\rho_{ND}]$	$(I_\rho)\,\mathbb{E}_s[\rho_{tot}]$	$\lvert\mathbb{E}_s[\phi]\rvert$
Baseline 0 MW/DER	Current	N/A	1	0.9973613	0.9990468	0.9981417	0.00168550
	RCP 4.5	N/A	1	0.9921395	0.9967424	0.9942708	0.00460286
	RCP 8.5	N/A	1	0.9870307	0.9943310	0.9904056	0.00730035
Case I 2 MW/DER	Current	[15, 17, 20]	1.005	0.9985411	0.9990471	0.9987823	0.00050595
	RCP 4.5	[5, 14, 15]	1.006	0.9959964	0.9967463	0.9963691	0.00074986
	RCP 8.5	[15, 18, 20]	1.005	0 9935877	0.9943750	0.9939963	0.00078736
Case II 3 MW/DER	Current	[15, 19, 25]	1.006	0.9989993	0.9990546	0.9990250	0.00005527
	RCP 4.5	[5, 19, 21]	1.005	0.9968660	0.9968663	0.9968926	0.00000027
	RCP 8.5	[15, 21, 24]	1.001	0.9948732	0.9948735	0.9948964	0.00000028
Case III 5 MW/DER	Current	[16, 19, 30]	1	0.9993408	0.9993410	0.9993408	0.00000012
	RCP 4.5	[8, 19]	1.006	0.9972468	0.9972468	0.9972585	0.00000008
	RCP 8.5	[3, 9, 13]	1.006	0.9959789	0.9959796	0.9960421	0.00000068
$\mathbb{E}_s[\rho_D]$	Expected ratio of delivered energy over energy demand in disadvantaged communities						
$\mathbb{E}_s[\rho_{ND}]$	Expected ratio of delivered energy over energy demand in non-disadvantaged communities						
Optimal weighting factor	Optimal weighting factor applies to disadvantaged communities only						

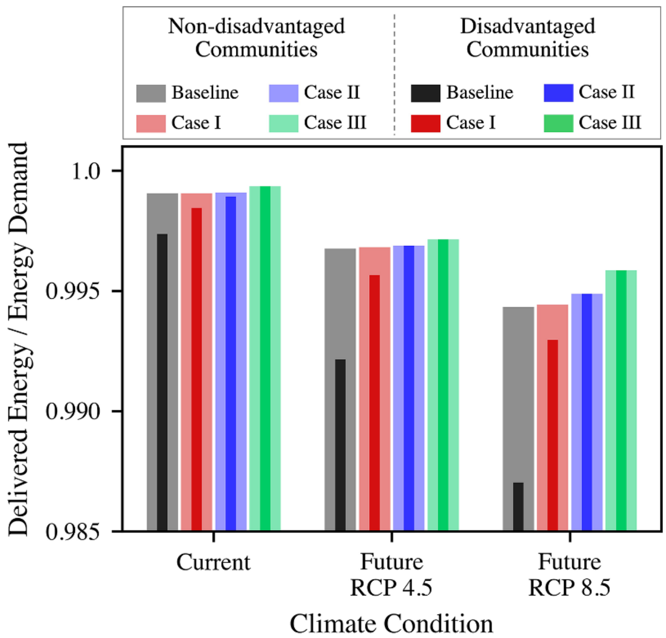

Figure 4. The ratio of delivered energy to energy demand under different climate conditions for the DER size of 2 MW (Case I), 3 MW (Case II), and 5 MW (Case III) with the weighting factor of 1.

considerations. As seen in all cases, climate change undermines the resilience index of the grid (represented by the ratio of delivered energy to energy demand). Further, the results demonstrate a considerable EGGR in the preadaptation condition. The preadaptation disparity only worsens under a changing climate. The adverse impact of climate change disproportionately affects the DAC. This argument can be substantiated by examining the slope of each line in the bottom figure of figures 4–7. The steeper the slope, the worse the impact of climate change on grid resilience. For all preadaptation cases, the line showing the results for the DAC is much steeper than the line for the non-DAC. This implies that the adverse effect of climate change is more pronounced for the DAC. The post-adaptation lines of disadvantaged and non-disadvantaged

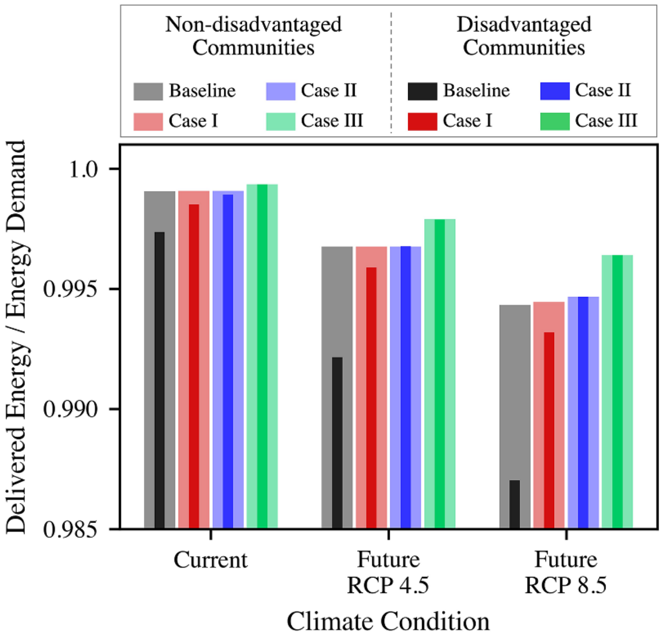

Figure 5. The ratio of delivered energy to energy demand under different climate conditions for the DER size of 2 MW (Case I), 3 MW (Case II), and 5 MW (Case III) with the weighting factor of 1.002.

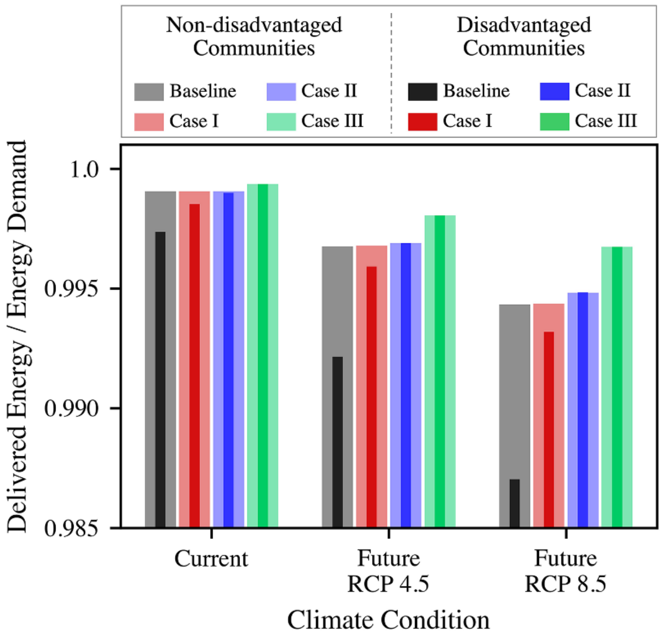

Figure 6. The ratio of delivered energy to energy demand under different climate conditions for the DER size of 2 MW (Case I), 3 MW (Case II), and 5 MW (Case III) with the weighting factor of 1.004.

communities have almost identical slopes, implying no disparity in the post-adaptation cases is achieved by employing the proposed approach. In all cases, optimal DER placement improved the grid resilience against flooding. Although the improvements in the defined resilience index might appear small, such enhancements in the expected annual resilience of the power grid can save millions of dollars (Dehghani *et al* 2021). For instance, it was shown that a 0.038% decrease in the expected annual resilience of an electric power system might result in economic losses of up to 83 million dollars per year (Ouyang *et al* 2014).

7. Discussion

Resilience enhancement measures are commonly categorized into hardening and operational strategies (Panteli *et al* 2015, Hassan *et al* 2022). Grid hardening measures mainly aim at making the grid stronger

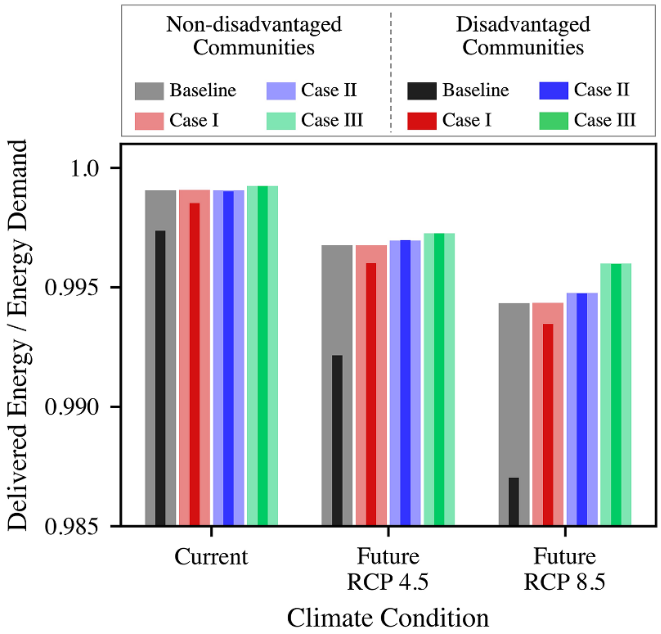

Figure 7. The ratio of delivered energy to energy demand under different climate conditions for the DER size of 2 MW (Case I), 3 MW (Case II), and 5 MW (Case III) with the weighting factor of 1.006.

against extreme events. More specifically, these measures are primarily designed to make the system less vulnerable by mitigating the probability of failure of critical components. For example, elevating substations and increasing the height of levees are effective hardening strategies for transmission systems susceptible to flooding. Operational strategies mainly aim at making the grid smarter by improving the operational capability of a power system, particularly in response to an extreme event. DER installation, microgrid formation, and recovery management are among the key operational measures. Further, renewable energy resources (Hassan *et al* 2022) can offer a viable alternative for enhancing grid resilience to the new patterns of extreme events. DERs can generally be integrated at three levels of application including small building level, district level, and urban level (Nadeem *et al* 2023). DERs commonly encompass microgenerators such as diesel generators, fuel cells, photovoltaic panels, and wind turbines, as well as energy storage devices such as flywheels, supercapacitors, and batteries (Li *et al* 2017).

The focus of the case study in this paper is on DER installations at urban level as an effective adaptation strategy. However, the proposed framework is general and can incorporate other measures. The presented method is scalable and transferable and can be applied along with other adaptation measures. Given the complexity of the problem and considering available data and resources, a number of simplifying assumptions were made in this study to enable the implementation of the research methodology. Future studies are recommended to address these assumptions and limitations. Due to the lack of access to the data of real power networks, the proposed framework in this study was applied to a modified IEEE standard test system. While the IEEE test systems are reliable for benchmark studies and research, full-scale power networks are quite larger and require further consideration. It is recommended for future studies to examine the application and efficacy of the proposed methodology with a full-scale power network. This will allow for verifying the scalability of the proposed modeling framework. This can be feasible through a close collaboration between research teams and local and regional electric companies.

The proposed methodology can be employed along with other steps to move toward equity and environmental justice for developing climate adaptation strategies for power grids. The proposed methodology and findings of this study directly contribute to the successful implementation of the recent Infrastructure law and Justice40. As an inevitable step in any effort to promote equity, the proposed method starts by identifying priority areas and disadvantaged communities within the study area that need to be prioritized. The next step involved delineating the flood risk of the power grid under the current and future climate conditions by examining flood hazards, vulnerability, and exposure. In the third step, the optimal adaptation strategy was sought with the goal of maximizing the network resilience to flood-induced power outages while minimizing the disparity in the risk of power outages in disadvantaged communities. Any successful adaptation strategy must include and implement a proactive and practical community engagement plan to establish and maintain a two-way dialogue with community residents throughout the process. Such a plan aims to broaden public engagement in developing and implementing adaptation strategies. The feasibility of adaptation strategies must be evaluated based on technical considerations, socioeconomic attributes, and the voice of community members and stakeholders. Finally, potential positive and negative consequences of any adaptation strategy need to be communicated to the public, and their feedback should be considered in the final plan.

8. Conclusions

Adapting to a changing climate warrants developing methodologies and strategies to ensure the integrity of our aging infrastructure to the evolving risk of extreme events and natural hazards in the face of climate change. Emphasis needs to be made on prioritizing disadvantaged communities that are shown to be more vulnerable to the adverse effects of extreme events and natural hazards. This study presented a new framework for climate adaptation of power network systems to worsening flood patterns in a changing climate while advocating and integrating environmental justice and equity considerations. The study offered a new metric embarking on the equitable risk concept to quantify the EGGR flood-induced power outages in disadvantaged communities. The metric was then employed in an optimization problem to determine the optimal adaptation strategy concurrently yielding the highest flood resilience and the lowest disparity in flood-induced power outages. The application of the presented framework is illustrated for a levee-protected power network system in northern California. For this purpose, a modified IEEE 30-bus standard test system was overlaid on the map of levee-protected regions and disadvantaged communities. The flood hazard levels were obtained for each leveed-protected region under current and projected future climate scenarios. The climate adaptation plan was developed by optimizing the placement of DER based on the resilience and environmental justice criteria. When optimizing the DER placement, disadvantaged communities were prioritized by assigning weight to their energy demand with the goal of avoiding energy disparity after the adaptation.

Energy equity is critical to developing equitable climate adaptation strategies for the nation. The presented framework is among the first attempts in the literature to provide utility companies, decision-makers, and other stakeholders with a robust tool for incorporating environmental justice in climate adaptation strategies of power network systems. Addressing emerging issues at the intersection of climate change and environmental justice requires close collaboration among local and state authorities, federal agencies, utility companies, as well as engineering, and scientists across various disciplines. A key element throughout the process is to establish effective and practical measures for community engagement to ensure the voice of communities is heard and directly implemented in climate adaptation strategies.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary information files).

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