A Geospatial Framework Using Multicriteria Decision Analysis for Strategic Placement of Reserve Generators in Puerto Rico

Susan M. Kotikot, Bandana Kar, and Olufemi A. Omitaomu, *Senior Member, IEEE*

***Abstract*—Extreme events such as hurricanes cause damages to various infrastructures, including power supply and transportation networks. Restoration of power supply services after extreme events is crucial for disaster response and recovery activities. With damages to transportation and other supply chain networks following extreme events, energy utility companies face significant challenges in achieving faster restoration of power supply services. This was the case for the utility companies in Puerto Rico after Hurricane Maria in 2017. One option for the utility companies in such circumstances will be to temporarily connect impacted populations to reserve generators, strategically located before the event, for quicker restoration of services. The objectives of this article are to: 1) develop a geospatial framework using a multicriteria decision analysis (MCDA) approach for placement of reserve generators and 2) identify strategic locations using 12 criteria representing physical, socioeconomic, environmental, and built environment conditions in Puerto Rico for the placement of reserve generators. Five different approaches are used to determine weights for the 12 criteria used in the MCDA approach. The geospatial framework developed in this article is comprehensive, which along with the weight determination approaches could be adapted to identify potential sites for the placement of additional energy infrastructures, including transformers, mobile stations, and microgrids, to power a city during extreme events.**

***Index Terms*—Energy infrastructure siting, geospatial framework, multicriteria decision analysis (MCDA), weighted sum model (WSM).**

I. Introduction

ENERGY infrastructure failure during extreme events involves destruction of power lines, transformers, generator stations, and substations. This inevitably results in power outages, whose severity depends on the strength and extent of the extreme event. Often, timely restoration of lost power is not possible due to: 1) nonfunctional transportation and communication infrastructures that prohibit accessibility and initial assessment of damage and 2) unavailability of any source of backup energy needed for initial response. Prolonged power outages affect the functionality of other critical infrastructures, such as communication, transportation, water, sanitation, health, and education. This adversely affects people's livelihoods, health, safety, and general well-being, thereby negatively impacting regional or national economy that can lead to long-term recovery.

This article is motivated by the problems encountered in Puerto Rico (PR) following hurricane Maria, a Category 5 hurricane, that made landfall on the island in September of 2017. The hurricane caused extensive damage to energy infrastructures. Lack of appropriate mechanisms to facilitate faster power restoration in PR left more than one and a half million habitants without electricity [1] and paralyzed majority of lifeline services, including health care and water supply. In fact, due to power loss, only three major hospitals in PR after hurricane Maria had access to electricity [2], 11% of community health centers were still closed four weeks following the hurricane [3], and 7% of habitants remained in darkness for more than six months [4]. In most cases, the power recovery process involved intermittent restoration of power in isolated locations, and the establishment of microgrids (for instance, PR Children's Hospital installed solar panels and a microgrid to generate electricity for the hospital) and battery-storage devices [5].

With mounting evidence about high probability of extreme events in the future, the United States Department of Energy recognizes the need for reserve generators, transformers, and mobile substations to expedite power restoration in the event of power supply disruptions. In addition to supporting the recovery process, reserve generators can sustain power supply to critical facilities and institutions, such as hospitals and evacuation shelters. Because multiple criteria influence the decision to identify strategic locations for the placement of these equipment, this article presents a multicriteria decision analysis (MCDA)-based geospatial framework that accounts for natural hazards (earthquakes, tornadoes, landslides, strong wind, and coastal flooding), physical characteristics of the island (slope, floodplain, and accessibility), and social characteristics (population density) to identify potential sites for placement of reserve generators in PR.

Manuscript received March 15, 2019; revised July 18, 2019, October 5, 2019, and December 1, 2019; accepted December 19, 2019. Date of publication March 6, 2020; date of current version July 16, 2020. This work was supported by the U.S. Department of Energy, Office of Electricity, under contract DE-AC05-00OR22725 with UT-Battelle, LLC. Review of this manuscript was arranged by Department Editor A. Solis. *(Corresponding author: Olufemi A. Omitaomu.)*

S. M. Kotikot was with the Oak Ridge National Laboratory, Oak Ridge, TN 37831 USA. She is now with the Department of Geography, Pennsylvania State University, University Park, PA 16802 USA (e-mail: malaso.susan@gmail.com).

B. Kar and O. A. Omitaomu are with the Oak Ridge National Laboratory, Oak Ridge, TN 37831 USA (e-mail: karb@ornl.gov; omitaomuoa@ornl.gov).

Color versions of one or more of the figures in this article are available online at https://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/TEM.2020.2964606

Using the framework, the following questions were answered in this article.

1) What percentage of PR is suitable for reserve generator placement?
2) What percentage of existing government institutions are suitably located within the identified potential areas?
3) What percentage of the existing power supply systems is suitably located to service critical facilities and supply power to the affected population?

To assess the sensitivity of the MCDA output, five different approaches were implemented to generate weights for the criteria, which included equal weighting, random weights, analytic hierarchy process (AHP), AHP with positive margin, and AHP with negative margin. The framework developed in this article could be used by decision makers, utility companies, and planners to assess the impact of each criterion on their final decision in identifying sites for placing reserve generation facilities. Also, this framework could significantly minimize power outage impact during future extreme events.

The rest of this article is organized as follows. The following section reviews related literature on MCDA and siting of energy infrastructures. In Section III, the framework implemented to evaluate suitability of locations for siting reserve generators is discussed. The results of the case study application of the framework are presented in Section IV followed by a discussion of the results in Section V. Section VI concludes this article.

II. Background

MCDA is used to make the best choice out of contradicting alternatives in the decision-making process. Primarily, MCDA allows ranking of alternatives based on a set of criteria, which requires weighting of each criterion based on certain constraints [6]. A significant number of approaches have been developed to evaluate the impact of criteria and weights on final decisions [7], [8]. Popular approaches include AHP [9], preference ranking organization method for enrichment evaluations [10], elimination et choix traduisant la realitè (elimination and choice expressing reality) [11], and multiattribute utility theory [11].

Because MCDA allows fragmentation of a problem into smaller parts, analysis of each part, and their integration into a desirable solution, it has been used in many disciplines, including finance [12], public policy [13], and spatial decision making that require the use of spatial criteria to achieve a final decision, such as resource management [14], emergency shelter siting [15], urban planning [16], [17], ecology [18], [19], and site suitability of humanitarian assistance projects [20], among others. Given that planning, operating, and policy actions in the energy sector require incorporation of economic, social, and environmental criteria, MCDA is also widely used in the energy sector as a decision-making tool [21]. It has been used for multichoice problems, such as selecting the most viable energy source as well as for elaborate projects involving evaluation of complete energy systems [22]–[25]. Other applications include evaluation of renewable or sustainable energy alternatives [11], [26]–[28], siting of solar farms [29], wind farms [30], and nuclear reactor plants [31].

Generally, MCDA is used to rank m alternatives based on n decision criteria. Each alternative A_i (for $i = 1, 2, \ldots, m$) is influenced by all the criteria C_j (for $j = 1, 2, \ldots, n$), and each criterion has a set of value scores V_k (for $k = 1, 2, \ldots, m$) and associated weight W_j (for $j = 1, 2, \ldots, n$). Typically, high weights imply high importance for a criterion. Once the criteria and their corresponding weights are determined, the next step in MCDA is aggregation, which provides an overall value for each alternative based on all criteria and their corresponding weights. The aggregation output could be described by a decision matrix $D \in \mathbb{R}^{m \times n}$. Each entry in the decision matrix a_{ij} corresponds to an alternative A_i, which is evaluated by multiplying each criterion with its corresponding weight.

The simplest form of MCDA is the weighted sum model (WSM), which implements an addition function such that each alternative A_i is derived by adding the multiplied output of a criterion C_j and its corresponding weight W_j as

$$A_i = \sum_{j}^{n} C_j \times W_j. \tag{1}$$

In this article, a variation of WSM [known as weighted linear combination (WLC)] approach was implemented to determine suitable locations for siting power reserve generators [32]. In this approach, (1) is multiplied with each exclusionary criterion with Boolean values (0 or 1) C_{bj}

$$A_i = \sum_{j}^{n} C_j W_j . \Pi C_{bj}. \tag{2}$$

III. Data and Methodology

Severe storms are the costliest extreme weather events in the United States, and they cause significant damage to energy infrastructures. In fact, storm-induced power outages cost an estimated 20–55 billion dollars annually [33]. Following the 2011 tornado outbreak that caused widespread damages in the south and central states (i.e., Alabama, Mississippi, Georgia, and Tennessee), it took the Tennessee Valley Authority about 65 days to restore power to more than 800 000 homes and businesses [34]. Hurricane Harvey (August 2017) left over two million residents without power in Texas [35], and after hurricane Maria (2017), several transmission and generation facilities were nonfunctional until May 2018 in PR [35].

Strategic placement of reserve generators is a viable option to ensure continued power supply following extreme events. However, the placement of these equipment requires a thorough assessment of physical, environmental, technical, and socioeconomic factors that may present conflicting objectives. The initial step in MCDA implementation involves the identification of criteria that are crucial for determining suitable sites. The selection of criteria depends on the specific facility under study as well as the purpose of the study. For instance, a wind farm should be sited in a place experiencing strong winds, and a nuclear plant should be located near water resources for cooling purposes. For this study, a comprehensive review of published literature, such as journal articles, authoritative reports, and siting guidelines, was conducted to identify potential criteria.

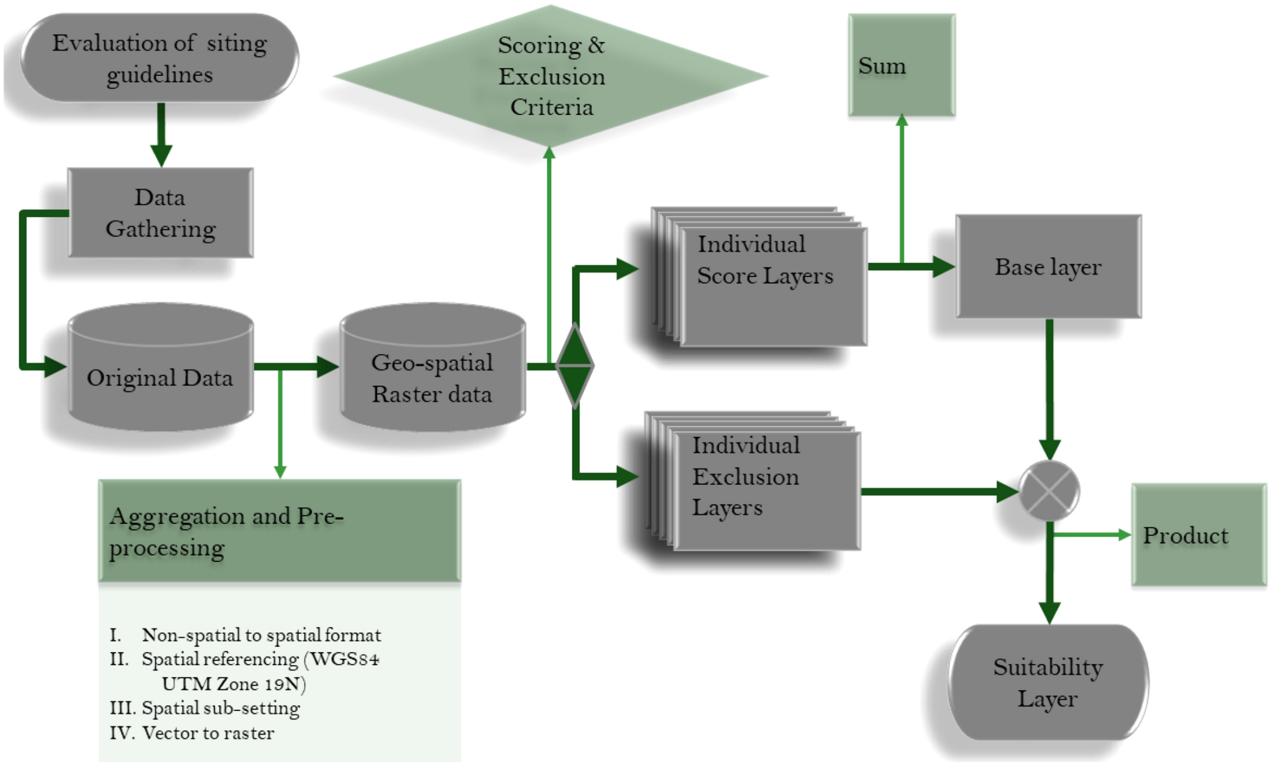

Fig. 1. Framework for site suitability assessment.

TABLE I
FACTORS CONSIDERED FOR GENERATOR SITING

	Category	Metrics	Factor
1	Natural Hazards	Measure of vulnerability to extreme events	1. Earthquakes 2. Landslides 3. Tornadoes 4. Winds 5. Storm Surge • Inundation probability • Elevation above high tide • Distance from coastline
2	Physical Characteristics	Measure of physical environmental hazard	1. Slope 2. Flooding • Wetlands • Flood zones
3	Protected lands	Measure of unavailability of land/assets	1. Parks, National monuments. National Forests, Wilderness areas, Wild/Scenic rivers, Wildlife refuges, American Indian Reservations
4	Socio-economic Characteristics	Measure of land use	1. Population Density
5	Transportation	Measure of accessibility	1. Roads (primary and major highways) 2. Train Stations 3. Sea Ports
6	Potential Existing Facilities	Measure of existing facilities suitability	1. Hospitals, Colleges, Airports, Military bases, Prisons

Fig. 1 describes the work flow implemented using WLC to identify potential sites for the placement of reserve generators.

A. WLC Approach

Spatial datasets corresponding to the criteria (see Table I) were obtained from different sources and converted to 30 m $\times$ 30 m raster layers for easy deployment of the approach. Based on the attributes, each spatial layer representing a criterion was classified into six suitability levels based on certain thresholds, with 0 being unsuitable and 5 being most suitable. The classification thresholds were selected based on the recommendations provided for site suitability in policy documents, journal articles, user manuals, and other authoritative reports [31], [36]. Based

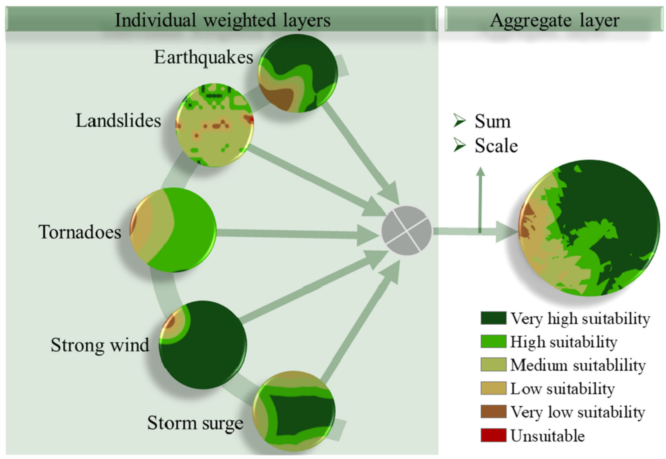

Fig. 2. Natural hazards used to assess site suitability.

on literature review, some criteria were also considered to be exclusionary and were classified into binary values (suitable being "1" and unsuitable being "0"). Due to lack of guidelines regarding how to rank the criteria, each criterion was considered to be equally responsible (weight of 1 was assigned to each criterion). Finally, all the ranked layers were combined to create the base layer representing total suitability score at each pixel using (1). The resulting base layer was then multiplied with the exclusionary criteria layers to eliminate unsuitable locations and derive a final suitability score for the entire island of PR.

B. Data Processing and Analysis

Key criteria identified for this study based on literature review (see Table I) included natural hazards, physical characteristics of a location, land use/cover characteristics, social characteristic (specifically, population concentration), and accessibility to transportation networks for transporting reserve generators to potential sites.

For geospatial implementation of the WLC approach, all datasets must be in geospatial format. Hence, the datasets that were obtained in Excel or CSV format were converted to point data layers using latitude and longitude information. All the spatial data layers were then projected to World Geodetic System 1984 Universal Transverse Mercator Coordinate System zone 19N spatial reference system to ensure coregistration among layers. Subsequently, all vector data layers were converted to 30 m $\times$ 30 m spatial resolution raster layers. This high spatial resolution ensured assessing suitability of locations without data loss across PR.

1) Natural Hazards: Fig. 2 depicts natural hazards used to determine site suitability, which included earthquakes, landslides, tornadoes, strong winds, and coastal flooding. To determine earthquake impacts, an earthquake dataset containing all earthquake events ranging in magnitude from 2.5 to 6.1 that occurred during 1950–2018 and their location was obtained from the United States Geological Survey (USGS) Earthquake catalogue [37]. Considering that an earthquake of magnitude 3.0 can be felt by people in high rise buildings, 423 earthquake events of magnitude 3.0 or greater were extracted. Using these 423 events, a kernel density function was implemented to calculate the density of the earthquake events. Using the earthquake magnitude as weight, which ensured that stronger events were given higher importance than weaker events, a search radius of 4 mi (calculated using a spatial variant of Silverman's Rule of Thumb) was used to compute earthquake density within 30 m $\times$ 30 m grid. The resulting earthquake density (number of earthquakes per 900 m^2) layer was classified into five levels (see Table II and Fig. 3).

For landslide events, a dataset of landslide events that occurred following hurricane Maria was obtained from the USGS Landslide Hazard Program [38] as a gridded dataset that depicted landslide density (number of landslides that occurred within 4-km^2 grid area). The dataset contained four categories of observations: no data, no landslide, less than 25 landslides per square kilometer, and more than 25 landslides per square kilometer. The high-risk landslide areas (with more than 25 landslides per square kilometer) were extracted. To ensure consistency in spatial resolution, a nearest neighbor algorithm was applied to this extracted dataset to transform the data into 30 m $\times$ 30 m spatial resolution while maintaining the cell values, which resulted in the landslide density surface (number of landslides per 900 m^2). The resulting landslide density layer was then classified into six suitability levels (see Table II and Fig. 3).

To assess impacts of tornadoes, historical records of tornadoes that occurred during 1950–2017 were obtained from the National Oceanic and Atmospheric Administration's (NOAA) Severe Weather Database [39]. Using the tornado touch down location, a kernel density function was applied to determine hot spots of tornadic events at 30 m $\times$ 30 m spatial resolution. Because all the recorded tornadoes were of category EF1 (Enhanced Fujita (EF) Scale), all observations were weighted the same. The resulting tornado density layer (number of tornadoes per 900 m^2) was reclassified into five suitability levels with high density areas being least suitable (see Table II and Fig. 3).

Strong winds can and tend to cause falling of trees, displacement of power lines, and damages to structures and infrastructures. Hence, to identify areas susceptible to strong winds, a record of wind events for the 12-year period between 2005 and 2017 was obtained from NOAA's Severe Weather Database [39]. The dataset contained wind speeds for all the events ranging from 34 to 61 mi/h, which is lower than the sustained wind speed of an EF0 tornado (65 mi/h). Although an EF0 tornado may only lead to minor damages, depending on the strength and age of buildings, the damages could be extensive. Based on this information, density analysis was conducted using all wind events with wind speed higher than 50 mi/h. The resulting wind event density layer (number of events per 900 m^2) was then reclassified into five suitability levels (see Table II and Fig. 3). Although no sites were excluded based on susceptibility to wind impacts, locations closer to high wind speed events were ranked low suitability.

Due to the extended coastline, the entire island is at a higher risk of experiencing storm surge due to tropical storms, tsunamis, etc. To assess storm surge risk for the island, two steps were implemented. First, a dataset depicting the maximum inland

TABLE II
CLASSIFICATION CRITERIA USED TO RANK FACTORS

	0 Unsuitable	1 Very Low Suitability	2 Low Suitability	3 Medium Suitability	4 High Suitability	5 Very High Suitability
Earthquake (number/900m^2)	>0.394	≤0.394 - >0.315	≤0.315 - >0.236	≤0.236 - >0.158	≤0.158 - >0.079	≤0.079 - 0
Tornado (number/900m^2)	>0.011	≤0.011 - >0.0074	≤0.0074 - >0.0045	≤0.0045 - >0.0021	≤0.0021 - >0.00054	≤0.00054 - 0
Landslide (number/900m^2)	>2.999	≤2.999 - >2.5	≤2.5 - >2.0	≤2.0 - >1.5	≤1.5 - >1.0	≤1.0 - 0
Wind (number/900m^2)	> 0.421	≤0.421 - >0.311	≤0.311 - >0.221	≤0.221 - >0.131	≤0.131 - >0.043	≤0.043 - 0
Distance to Shoreline (miles)	≤2.0	>2.0 - ≤4.0	>4.0 - ≤6.0	>6.0 - ≤8.0	>8.0 - ≤10.0	>10.0
Slope (degrees)	>22.5	≤22.5 - >20.0	≤20.0 - >15.0	≤15.0 - >10.0	≤10.0 - >5.0	≤5.0 - 0.0
Population Density (persons/km^2)	0	>0 - ≤2,000	>2,000 - ≤5,000	>5,000 - ≤15,000	>15,000 - ≤30,000	>30,000

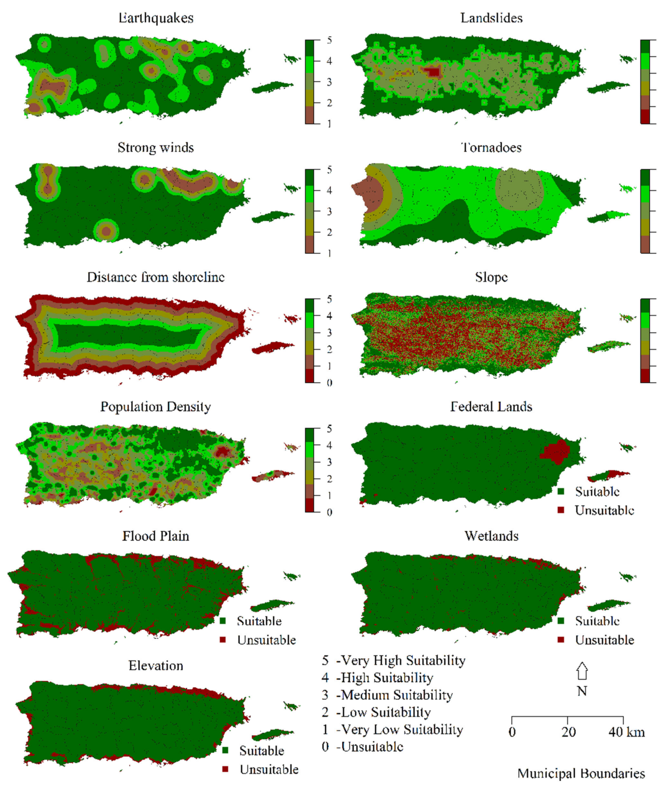

Fig. 3. Ranked spatial layers for all site suitability factors.

extent of a storm surge during a worst-case scenario was obtained from the NOAA. This dataset was generated by using the Sea, Lake, and Overland Surge from Hurricanes model and depicted the height of a storm surge along the coastal areas of PR [40]. According to this dataset, areas within 15-ft height above mean sea level were found to be at a higher risk of experiencing storm surge impacts. Second, using digital elevation data and 15 ft as the threshold, a binary layer was created such that locations at elevations greater than 15 ft were classified as suitable and the locations at elevations equal to or below 15 ft were classified as unsuitable (see Fig. 3).

There are areas along the coastline that can be inaccessible even though not inundated during and following a tropical storm. To eliminate these areas, inland areas within 2 mi of the coastline were regarded as unsuitable, and areas beyond two miles were assigned higher suitability with increasing inland distance at 2-mi increments (see Fig. 3). Elevations of the areas within this exclusion zone are either below or equal to 15 ft.

2) Physical Characteristics: Unlike the central region, the coastal part of PR has flat terrain, which is prone to flooding. To assess flood risk, two approaches were implemented. First, the National Flood Hazard Layer obtained from the Federal Emergency Management Agency [41] was used to identify flood plain areas. Using this dataset, areas designated as 100-year flood plain zones were considered to be unsuitable, and areas beyond the 100-year flood plain zone were classified to be suitable. Second, all areas identified as water or wetland in the land cover layer obtained from the Multiresolution Land Characteristics Consortium's National Land Cover Database were classified as unsuitable (see Fig. 3).

Areas with steep slopes tend to be prone to landslides. Furthermore, installation of generators in these areas will require transportation of heavy equipment along the uphill areas, which can be time consuming and expensive. To eliminate areas with steep slopes from being considered for locating reserve generators, a slope (degrees) layer was generated at 30 m × 30 m spatial resolution using digital elevation data, which was classified into six suitability levels (see Table II and Fig. 3). Flat to gently sloping terrain was preferred and ranked highly while steeper slopes were deemed unsuitable (see Fig. 3).

3) Protected Lands: Federal lands are governed by specific regulations about construction and any form of development. These lands were, therefore, classified as unsuitable and excluded from consideration as potential sites. Geospatial data representing boundary limits for specific federal lands (see Table I) were obtained from the USGS small-scale data catalog [42], the United States Fish and Wildlife Services [43], and the U.S. Forest Service [44]. Each vector layer representing a specific type of federal land (national park or wildlife) was converted to a raster layer at 30 m × 30 m spatial resolution. All the layers representing federal lands were merged to create a single raster layer representing unsuitable areas (see Fig. 3).

4) Socioeconomic Characteristics: Although it is recommended that certain energy generators such as nuclear reactors be located away from populated areas [31], [45], [46], there is no clear guideline for locating reserve generators, nor are

TABLE III
EXCLUSIONARY CRITERIA USED TO DETERMINE UNSUITABLE SITES

	Category	**Consideration**	**Measure**	**Exclusion Criteria**
1	Natural Hazards	Landslides	Probability of landslide occurrence	Areas with >25 recorded landslides per km^2
2	Physical Characteristics	Storm Surge	Elevation above normal high tide level and Euclidean distance from the coastline	Areas that are $\leq$ 15 ft below normal high tide and areas within 2 miles of the coastline
		Flooding	Location within wetlands and probability of flooding	All areas classified as wetlands or open water and all areas within the 100-year flood hazard zone
		Earth Failure and Mobility	Topographic slope (Degree of steepness)	All areas > 22.5 degree
3	Protected lands	Land use restrictions	Location within protected lands	Areas inside of designated protected or ecological lands
4	Socio-economic characteristics	Population density	Number of persons within a mile radius	Areas with 0 persons within a mile radius

there stated health risks associated with a generator. Since the purpose of the reserve generators is to ensure availability of power during an emergency, suitable areas were defined by high population density. The LandScan high-resolution population dataset [47] provided by the Oak Ridge National Laboratory at approximately 90 m $\times$ 90 m spatial resolution was resampled to 30 m $\times$ 30 m spatial resolution to match the rest of the data layers. Using the resampled population density layer (number of people within 900 m^2), a focal sum was performed to determine the total population within a 1-mi radius of each grid cell. From the resulting population density layer (number of people within 8.13 km^2), all grid cells with a value of zero were classified as unsuitable, and remaining grid cells were classified into five suitability levels according to the thresholds in Table II, giving more preference to areas with higher population concentration (see Fig. 3).

5) Transportation: Ideally, a selected site should be accessible through multiple modes of transportation in case 1 or the other is damaged during an extreme event. In PR, roads are the major mode of transportation, and to a limited extent, rail is used in the city of San Juan. Transportation routes were assessed following the guidelines outlined by the IEEE [48]. As per the guidelines, qualified roads for transporting heavy energy equipment should: 1) meet dimension clearance for oversized equipment; 2) not exceed the maximum allowable axle load; and 3) be solid and all weatherproof. Because detailed data were not available for such evaluation, road network center lines were adjusted to determine widths according to the following specifications provided by the Federal Highway Administration [49]: freeway (12 ft/3.6 m wide), one-lane ramps (12–30 ft/3.6–9.2 m wide), arterial and collector roads (10–12 ft/3.3–3.6 m wide), and local roads (9–12 ft/2.7–3.6 m wide). All the locations within 100 m from the shoulders of primary roads (freeways) were classified as suitable, while other areas were classified as unsuitable.

6) Potential Facilities: In order to eliminate the cost of building a new site for reserve generators, existing government facilities were evaluated for their site suitability. Colleges and universities, prisons, hospitals, and military bases were considered as potential facilities because, often, they serve as refuge to people during disasters, and they provide critical services for continued functioning of a society. Having reserve generators in these facilities ensures that most of the impacted population will have access to power. However, these facilities are usable only if their location meets suitability criteria discussed above, and/or existing structures are designed to withstand possible extreme events. Vector layers for all potential facilities were converted to 30 m $\times$ 30 m spatial resolution raster layers, which were then evaluated for their suitability using the final suitability scores (see Figs. 8 and 9).

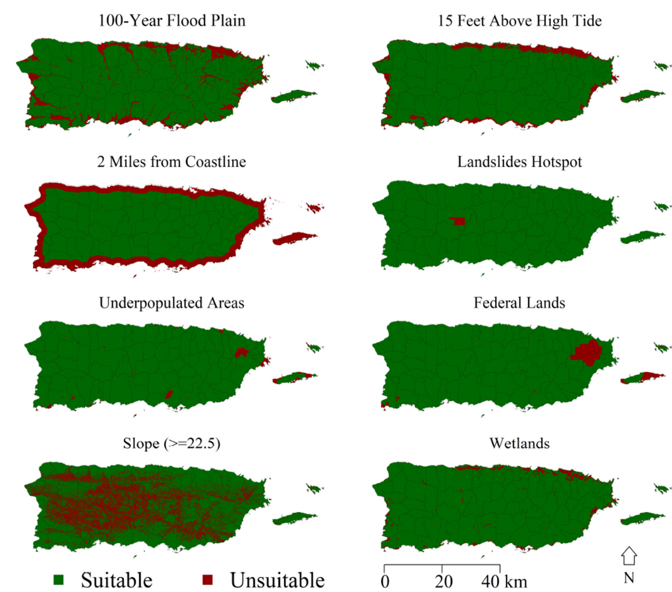

Fig. 4. Spatial layers showing exclusion zones.

7) Exclusionary Criteria: Exclusionary criteria were used to eliminate locations that failed to meet set guidelines or presented conflict for placement of the reserve generators. Table III lists the exclusionary criteria that were used to identify undesirable sites, as shown in Fig. 4.

Each exclusionary criterion was multiplied with the base layer resulting from (1) using (2) to eliminate unsuitable locations and derive an overall suitability score. This process is illustrated in Fig. 5, where each small square is a 30 m $\times$ 30 m grid area on the ground represented as a pixel on a gridded layer for the criterion C_j or FR_i (for $i = 1, 2, \ldots, m$) or exclusionary criterion C_{bj} or FC_i (for $i = 1, 2, \ldots, m$) being considered. FR or

TABLE IV
RANDOM WEIGHTS GENERATED FOR EACH CRITERION

	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**Avg**
Earthquakes	3	6	1	4	4	4	4	6	5	2	7	3	7	10	4	5
Landslide	3	7	1	3	2	8	1	10	7	7	5	7	7	8	4	5
Tornadoes	7	7	6	1	7	1	5	6	4	3	2	10	6	8	1	5
Winds	3	9	5	7	2	4	4	1	5	3	8	6	6	10	8	5
Elevation above high tide	10	7	7	4	5	5	6	5	5	9	3	4	1	4	6	5
Distance from Coastline	3	2	2	1	10	5	3	6	4	6	2	3	1	3	6	4
Slope	6	4	1	3	8	5	5	4	8	6	8	5	6	10	5	6
Wetlands	8	3	1	9	7	5	1	6	6	3	10	5	7	5	7	6
Floodplain	9	4	6	2	4	2	10	4	2	2	4	1	6	7	3	4
Protected lands	8	1	2	8	6	6	10	9	2	9	8	5	8	9	4	6
Population	10	1	2	6	4	2	1	3	3	1	4	2	3	4	3	3
Potential facilities	8	7	6	5	9	5	9	1	7	5	4	4	10	6	4	6

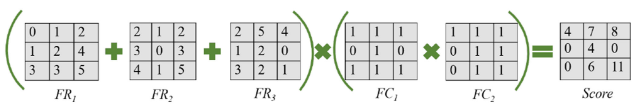

Fig. 5. Schematic illustration of the GIS multicriteria approach for gridded data layers.

$Factor Rating$ represents each factor that was used to determine site suitability (e.g., natural hazards, population density, etc.), and FC or $Factor Constraint$ corresponds to each exclusionary criterion used to generate the final suitability layer.

C. Sensitivity Analysis

It was assumed that all the criteria influencing the placement of reserve generators are equally important. Nonetheless, it is evident from the analysis that some criteria, such as distance from the coast or proximity to populated areas, are more important than others in determining the best site for reserve generator placement. A sensitivity analysis was conducted using four different sets of weights for the criteria. First, a random weight generation approach was implemented such that for each criterion, 15 normally distributed random numbers between 1 and 10 were generated to represent expert weights [50], [51]. Similar to equal weighting, this approach assumes no prior information about the importance of a criterion [50]. The 15 randomly generated weights were then averaged to obtain an average weight for each criterion. Table IV represents the random weights generated for each criterion. Each individual criterion layer was then multiplied by its corresponding weight, and the resulting layers were then combined together using (1) to generate the suitability layer.

In the second approach, the AHP was used to determine weights for the criteria. Based on historical data for each criterion, pairwise ranks were generated for a pair of criteria. Each criterion was ranked against the remaining criteria on a scale of 1–9, such that the criteria with high likelihood of influencing suitability were ranked higher. Table V shows the weights computed for each criterion using a pairwise comparison matrix. Given that some criteria are more important than others as stated above, the positive and negative margins for each criterion's computed weight from Table V were also determined (%weight +/− %margin) following the discussion and AHP template provided by Goepel [52]. Finally, three more suitability layers were created using the pairwise based weight and the pairwise weight with positive and negative margins using (1).

TABLE V
WEIGHTS GENERATED BASED ON THE AHP PAIRWISE COMPARISON MATRIX

Criterion	**Weight**	**Margin**
Landslide	10.10%	5.90%
Earthquake	3.50%	1.40%
Tornado	2.00%	0.90%
Wind	2.00%	0.90%
Distance to coastline	28.50%	16.80%
Population	34.70%	20.70%
Slope	19.10%	6.20%

IV. RESULTS

This section presents the results of the analyses for PR and displays maps depicting the spatial distribution of suitable sites and suitable facilities across the island.

A. Site Suitability for Placement of Reserve Generators

The base layer shown in Fig. 6 represents the total suitability score of sites across the island calculated by aggregating all the evaluated factors in Fig. 3 and using the equal weight approach. Summation of all the ranked layers resulted in total scores ranging between 3 and 55. These scores were classified into five suitability categories such that differences between categories were maximized by placing boundaries between classes, where values relatively differ [53]. Higher scores in the base layer indicate high suitability of locations for siting of reserve generators.

Aggregation of exclusion layers resulted in a single exclusion layer depicting unsuitable sites that failed to meet the criteria for suitability.Fig. 7 shows the spatial distribution of suitable and unsuitable locations based on the exclusionary criteria. According to this layer, unsuitable locations are present along the coast as well as along the central and northeastern part of the island.

The final suitability map (see Fig. 8) is a product of the base layer (see Fig. 6) and the exclusion layer (see Fig. 7). The map shows potential siting locations at five suitability levels

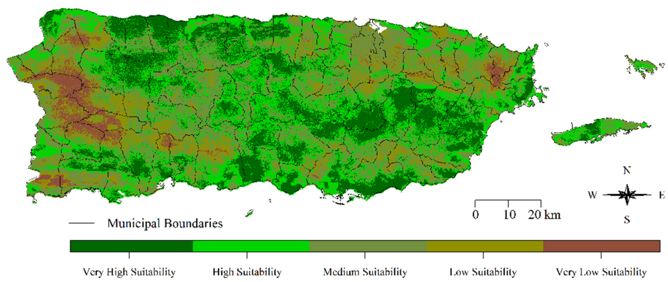

Fig. 6. Site suitability layer without exclusionary factors.

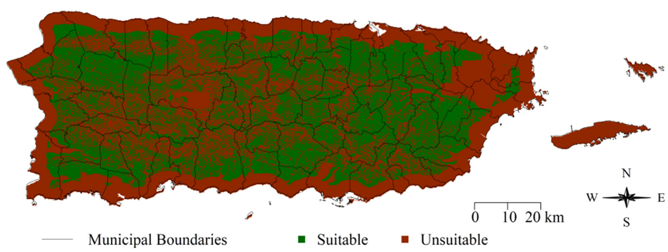

Fig. 7. Final exclusionary layer.

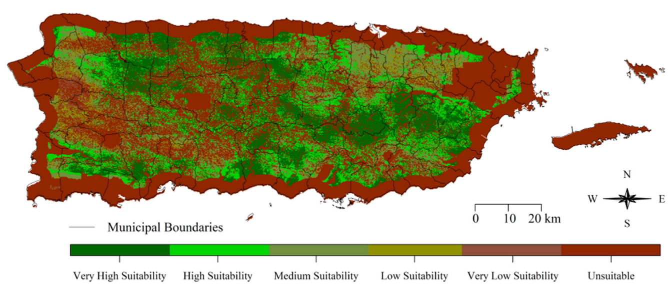

Fig. 8. Final site suitability layer.

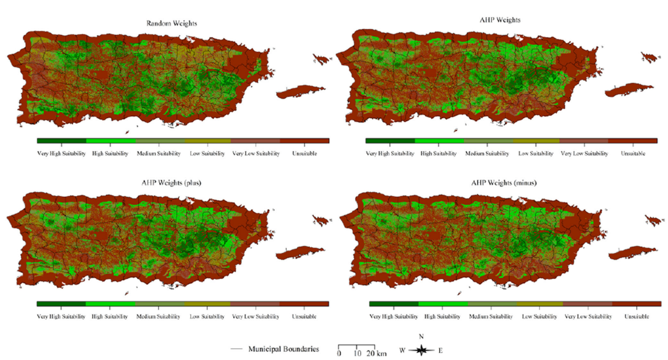

Fig. 9. Site suitability layer using different weights.

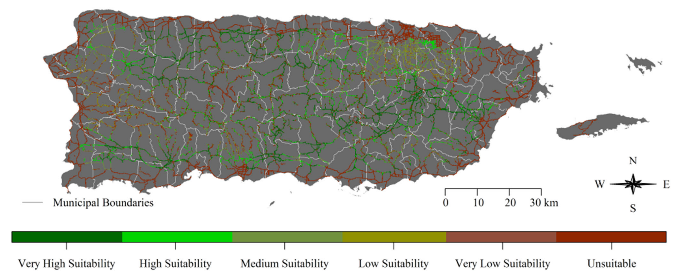

Fig. 10. Accessible sites within 100 m of primary roads.

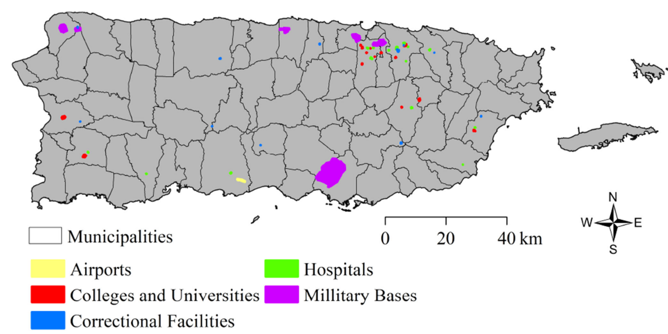

Fig. 11. Suitability of existing government facilities.

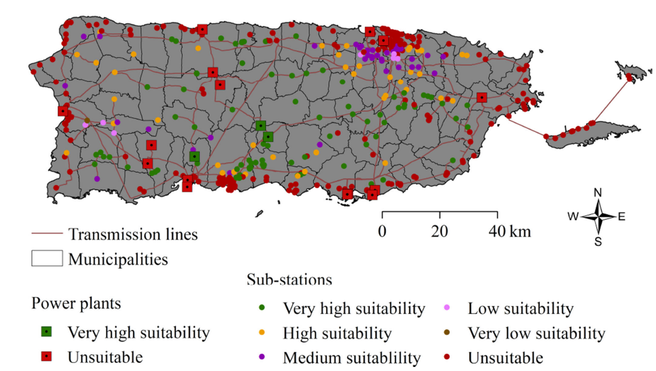

Fig. 12. Suitability of existing energy infrastructures using equal weights.

as well as the unsuitable locations. The locations with very high suitability present least challenges for placement of reserve generators as opposed to the locations with very low suitability although these locations are not totally unsuitable. Fig. 9 depicts the final suitability layers created for PR using random weights and AHP-derived weights (discussed above).

Using the final suitability layer, suitable and accessible sites were evaluated based on their proximity to a primary road. Suitable areas within 100 m of a primary road are considered viable for placement of reserve generators. Fig. 10 shows areas within 100 m of primary roads that can be used for reserve generators.

B. Site Suitability of Government Facilities

Government facilities with at least half of their land area located within suitable sites were identified as potential sites for reserve generators. Fig. 11 shows the location of these facilities, most of which are present around the city of San Juan with a few located on the southern and western parts of the island. There are barely any facilities in the central parts of PR suitable based on our approach.

C. Site Suitability of Existing Power Plants and Substations

According to the equal weights approach, only 16% existing power plants and 42% of substations are located in suitable areas (see Fig. 12). The suitability score determined by using random weights and the AHP approach also revealed that only

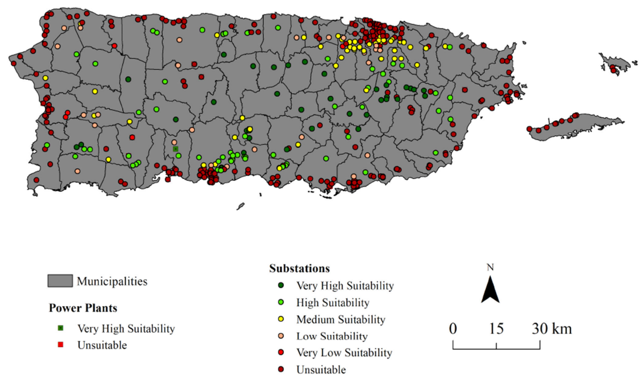

Fig. 13. Suitability of existing energy infrastructures using AHP weights.

16% of the power plants are located in suitable areas, and of the 461 substations, 23.4% and 11.7% are located in high and medium suitability locations, respectively (see Fig. 13). Most of the unsuitable plants and substations are located along the coastline; hence, they are at a higher risk of being impacted by storm surge, which can lead to extended power outage.

V. Discussions

Forty five percent of the PR land area was found to be suitable for placing reserve generators using the equal weights approach (see Fig. 8). This percentage did not change significantly using random weights and AHP generated weights (see Fig. 9). The major difference in suitable land area was found between the northern and southern parts of the island. While most of the north-eastern part of PR was found to have very low to low suitability based on equal weight and random weight approaches, the same areas were found to be highly suitable using the AHP approach. Likewise, most of the south-eastern part of PR was found to be unsuitable based on the AHP approach, but the same areas were found to be suitable based on the equal weights and random weights. However, according to the suitability score determined by the five approaches (equal weights, random weights, and AHP weights with positive and negative margin), the eastern half of PR is most suitable for placement of generators.

Of the suitable lands, about 14% is very highly suitable, 15% is highly suitable, 10% is moderately suitable, 3.3% has low suitability, and 0.8% has very low suitability. Most of the highly suitable sites are located along the eastern, north-western, and southern parts of the island. Sites around the city of San Juan were found to have medium to low suitability because of their presence in hazardous places prone to tornadoes, strong winds and earthquakes. All areas within two miles of the coastline are unsuitable. Four major factors, including storm surge risk, landslide hazard, slope, and protected lands, contributed the most in determining exclusion zones.

Accessibility of suitable sites is necessary to ensure smooth transportation of equipment both to and from the placement sites for installation. There is relatively equal road accessibility across the entire island of PR. Based on the accessibility analysis, all the suitable sites are within 100 m of a primary or major road, and hence, are accessible by a primary or a major road.

Government facilities, including colleges and universities, hospitals, prisons, airports, and military bases, can be used as alternate placement sites for reserve generators. These facilities are also accessible by roads and have the advantage of providing security and shelter to energy equipment. These facilities also serve a critical role in the continued functioning of society, as they can be used to provide shelters to local public during disaster events. Placing reserve generators in these facilities, therefore, will ensure that many of the sheltered people have access to power following an extreme event induced power outage. Based on the five weighting approaches used, from the available government facilities, six hospitals, four colleges and universities, and five correctional facilities were found to have very high suitability for siting reserve generators (see Fig. 11). For areas without any facility, new shelters could be built in suitable locations, and/or existing shelters in suitable sites could be retrofitted. Further analysis of existing facilities is needed to assess their structural conditions for retrofitting.

With most of the power plants and substations located in unsuitable areas, the energy infrastructures in PR are highly susceptible to extreme events. This is possibly the reason for the extended power outage that occurred following hurricane Maria in 2017. This study provides information about suitable sites based on several factors that could be used to minimize risk to existing power stations and in identifying sites for placement of reserve generators that are away from hazardous areas, but close to roads. This will help meet energy demand following extreme events as well as contribute to speedy recovery and restoration of energy infrastructures.

VI. Conclusion

In this article, an MCDA technique was employed to identify potential sites for power storage devices. Several factors were combined to determine site suitability across PR and identify suitable government facilities. Potential sites were ranked according to their suitability level based on the level of risk involved in selecting a site.

About 45% of PR land area was found to be suitable for siting reserve generators. With the exception of areas within 2 mi of the coastline, suitable sites are spread across the island with the eastern part of the island containing a significant amount of suitable land area. Based on the site suitability score (see Figs. 8 and 9), land areas surrounding the city of San Juan and along the south-western parts of PR were found to be unsuitable. In addition to the government facilities identified above to be highly suitable, nine hospitals, 11 colleges and universities, 11 correctional facilities, six military bases, and one airport were found to be moderate to highly suitable for placement of reserve generators. Most of these facilities are located in San Juan with a few located in the southern and western parts of PR. While only 16 and 42% of existing power plants and substations, respectively, are present in suitable areas (see Figs. 12 and 13), the majority of the power plants and substations are present along the coastline and, hence, are at a higher risk of being impacted by tropical storms and coastal flooding events. Of the assessed natural hazards, landslides and storm surges present the greatest risk to central and coastal PR respectively. Physical characteristics, specifically, slope and flood zones, offer the most challenges for siting in central and coastal parts of the island. Given that the highly populated areas are present in San Juan and along the coastline, there is a need for a systematic evaluation of placement alternatives to ensure that most people can have access to power in case of an extreme event.

The results of this study provides necessary information to guide the placement of reserve generators such that the associated costs are minimized while maximizing utility and mitigating potential risks to energy infrastructures. This article did not considered energy supply and demand, which are crucial to identifying the number of reserve generators needed, their capacity, and where they should be located with regard to population centers. Also, sparsely populated areas in the PR have very poor road accessibility, which increases the risk of these populations to potential long-term power outages. Future study will focus on: 1) energy supply and demand analysis; 2) development of a framework to determine number of storage devices and reserve generators needed to meet energy demand; 3) site suitability analysis of solar farms based on the criteria used in this study; and 4) exploring the impact of road accessibility on reserve generator placement such that actions can be taken to reduce damages to these facilities under certain conditions. Such information will help local agencies and decision makers implement strategic plans to ensure power supply in the case of extreme events.

Acknowledgment

This manuscript has been authored by UT-Battelle, LLC, under contract DE-AC05-00OR22725 with the US Department of Energy (DOE). The U.S. government retains the publisher, by accepting the article for publication, acknowledges that the U.S. government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this manuscript, or allow others to do so, for U.S. government purposes. DOE will provide public access to these results of federally sponsored research in accordance with the DOE Public Access Plan (https://energy.gov/downloads/doe-public-access-plan).

References

[1] United States Department of Energy, "Hurricanes Maria, Irma, and Harvey. Situation Report #48, Event Summary," 2017. [Online]. Available: https://www.energy.gov/sites/prod/files/2017/09/f37/Hurricanes Maria Irma Harvey Event Summary September 27.pdf

[2] J. Michaud and J. Kates, "Public Health in Puerto Rico after Hurricane Maria," The Henry J. Kaiser Family Foundation, 2017. [Online]. Available: http://files.kff.org/attachment/Issue-Brief-Public-Health-in-Puerto-Rico-after-Hurricane-Maria

[3] P. Shin, J. Sharac, R. Gunsalus, B. Leifer, and S. Rosenbaum, "Puerto Rico's Community Health Centers: Struggling to Recover in the Wake of Hurricane Maria," RCHN Community Health Foundation, 2017. [Online]. Available: https://publichealth.gwu.edu/sites/default/files/downloads/GGRCHN/GG%3ARCHN%20Policy%20Issue%20Brief%20%2350%20FV.pdf

[4] S. Aaronson, "Bureaucratic Challenges to Hurricane Recovery in Puerto Rico," Edison Electric Institute, 2018. [Online]. Available: https://oversight.house.gov/wp-content/uploads/2018/03/Aaronson-EEI_Testimony_03212018.pdf

[5] L. Gilpin, "Puerto Rico's solar future takes shape at children's hospital, with tesla batteries," *InsideClimateNews*, Oct. 2017.

[6] E. Jacquet-Lagreze and Y. Siskos, "Preference disaggregation: 20 Years of MCDA experience," *Eur. J. Oper. Res.*, vol. 130, pp. 233–245, 2001.

[7] C. Brugha, "Structuring and weighting criteria in multi criteria decision making (MCDM)," in *Trends in Multicriteria Decision Making* (Lecture Notes in Economics and Mathematical Systems), T. Stewart and R. van den Honert, Eds. Berlin, Germany: Springer, 1998.

[8] A. Cervantes and L. T. Biegler, "Optimization strategies for dynamic systems," in *Encyclopedia of Optimization*. Berlin, Germany: Springer, 2009, pp. 2750–2757.

[9] T. L. Saaty, "The analytic hierarchy process," *Eur. J. Oper. Res.*, vol. 48, pp. 9–26, 1990.

[10] J. Oberschmidt, J. Geldermann, J. Ludwig, and M. Schmehl, "Modified PROMETHEE approach for assessing energy technologies," *Int. J. Energy Sector Manage.*, vol. 4, no. 2, pp. 183–212, 2010.

[11] J.-J. Wang, Y.-Y. Jing, C.-F. Zhang, and J.-H. Zhao, "Review on multi-criteria decision analysis aid in sustainable energy decision-making," *Renew. Sustain. Energy Rev.*, vol. 13, no. 9, pp. 2263–2278, 2009.

[12] C. Zopounidis and M. Doumpos, "Multi-criteria decision aid in financial decision making: Methodologies and literature review," *J. Multi-Criteria Decis. Anal.—Optim., Learn., Decis. Support*, vol. 11, nos. 4/5, pp. 167–186, 2002.

[13] N. Mladineo, I. Lozić, S. Stošić, D. Mlinarić, and T. Radica, "An evaluation of multicriteria analysis for DSS in public policy decision," *Eur. J. Oper. Res.*, vol. 61, no. 1, pp. 219–229, 1992.

[14] J. P. B. Valverde, C. Blank, M. Roidt, L. Schneider, and C. Stefan, "Application of a GIS multi-criteria decision analysis for the identification of intrinsic suitable sites in Costa Rica for the application of managed aquifer recharge (MAR) through spreading methods," *Water (Switzerland)*, vol. 8, no. 9, 2016, Art. no. 391.

[15] B. Kar and M. E. Hodgson, "A GIS-based model to determine site suitability of emergency evacuation shelters," *Trans. GIS*, vol. 12, no. 2, pp. 227–248, 2008.

[16] M. A. Al-Shalabi, S. Bin Mansor, N. Bin Ahmed, and R. Shiriff, "GIS based Multicriteria approaches to housing site suitability assessment," in *Proc. XXIII FIG Congr. Shaping Change*, Munich, Germany, Oct. 8–13, 2006, pp. 1–17.

[17] J. Chen, "GIS-based multi-criteria analysis for land use suitability assessment in City of Regina," *Environ. Syst. Res.*, vol. 3, no. 1, 2014, Art. no. 13.

[18] K. Bunruamkaew and Y. Murayama, "Site suitability evaluation for ecotourism using GIS & AHP: A case study of Surat Thani Province, Thailand," *Procedia—Social Behavioral Sci.*, vol. 21, pp. 269–278, 2011.

[19] X. Zhang, Z. Wang, and J. Lin, "GIS based measurement and regulatory zoning of urban ecological vulnerability," *Sustainability (Switzerland)*, vol. 7, no. 8, pp. 9924–9942, 2015.

[20] B. M. E. Curran, Richard W., and H. M. Bell, "Multi-criteria decision analysis approach to site suitability of U.S. Department of Defense Humanitarian assistance projects," *Procedia Eng.*, vol. 78, pp. 59–63, 2014.

[21] B. F. Hobbs and P. M. Meier, *Energy Decisions and the Environment: A Guide to the Use of Multicriteria Methods*, 1st ed. Berlin, Germany: Springer, 2000.

[22] S. Cajot, A. Mirakyan, A. Koch, and F. Maréchal, "Multicriteria decisions in urban energy system planning: A review," *Front. Energy Res.*, vol. 5, 2017, Art. no. 10.

[23] D. Diakoulaki, C. H. Antunes, and A. Gomes Martins, *MCDA and Energy Planning*. New York, NY: Springer, 2005, pp. 859–890.

[24] K. Volkart, N. Weidmann, C. Bauer, and S. Hirschberg, "Multi-criteria decision analysis of energy system transformation pathways: A case study for Switzerland," *Energy Policy*, vol. 106, pp. 155–168, 2017.

[25] I. Wilkens and P. Schmuck, "Transdisciplinary evaluation of energy scenarios for a German village using multi-criteria decision analysis," *Sustainability*, vol. 4, no. 4, pp. 604–629, 2012.

[26] R. Abu Taha and T. Daim, *Multi-Criteria Applications in Renewable Energy Analysis: A Literature Review*. London, U.K.: Springer, 2013, pp. 17–30.

[27] H. Polatidis, D. A. Haralambopoulos, G. Munda, and R. Vreeker, "Selecting an appropriate multi-criteria decision analysis technique for renewable energy planning," *Energy Sources, Part B: Econ., Planning Policy*, vol. 1, no. 2, pp. 181–193, 2006.

[28] C. Wimmler, G. Hejazi, E. D. O. Fernandes, C. Moreira, and S. Connors, "Multi-criteria decision support methods for renewable energy systems on islands," *J. Clean Energy Technol.*, vol. 3, no. 3, pp. 185–195, 2015.

[29] Y. Solangi, Q. Tan, M. Khan, N. Mirjat, and I. Ahmed, "The selection of wind power project location in the southeastern corridor of Pakistan: A factor analysis, AHP, and fuzzy-TOPSIS application," *Energies*, vol. 11, no. 8, 2018, Art. no. 1940.
[30] T. P. Wissing, "Renewable ocean energy site selection using a GIS: Gulf coast potential," Ph.D. dissertation, Dept. Geography Geol., Univ. Southern Mississippi, Hattiesburg, MS, USA, 2013.
[31] O. A. Omitaomu *et al.*, "Adapting a GIS-based multicriteria decision analysis approach for evaluating new power generating sites," *Appl. Energy*, vol. 96, pp. 292–301, 2012.
[32] S. Drobne and A. Lisec, "Multi-attribute decision analysis in GIS: Weighted linear combination and ordered weighted averaging," *Informatica (Slovenia)*, vol. 33, pp. 459–474, Jan. 2009.
[33] Center for Climate and Energy Solutions, "Resilience strategies for power outages," Aug. 2018. [Online]. Available: https://www.c2es.org/site/assets/uploads/2018/08/resilience-strategies-power-outages.pdf
[34] D. Flessner, "TVA hardens transmission system to better weather the next storm," 2016. [Online]. Available: https://www.timesfreepress.com/news/local/story/2016/apr/24/tvas-hardens-transmissisystem-better-weather/361849/
[35] North American Electric Reliability Corporation, "Hurricane Harvey Event Analysis Report," Mar. 2018. [Online]. Available: https://www.nerc.com/pa/rrm/ea/Hurricane_Harvey_EAR_DL/NERC_Hurricane_Harvey_EAR_20180309.pdf
[36] R. J. Belles and O. A. Omitaomu, "Evaluation of potential locations for siting small modular reactors near federal energy clusters to support federal clean energy goals," Oak Ridge Nat. Lab., Oak Ridge, TN, USA, Tech. Rep. ORNL/TM-2014/433, 2014.
[37] United States Geological Survey, "ANSS Comprehensive Earthquake Catalog (ComCat)." [Online]. Available: https://earthquake.usgs.gov/data/comcat/, Accessed on: Jun. 15, 2018.
[38] E. K. Bessette-Kirton *et al.*, "Preliminary locations of landslide impacts from hurricane Maria, Puerto Rico," 2017. [Online]. Available: https://landslides.usgs.gov/research/featured/2017/maria-pr/
[39] NOAA National Weather Service, "Storm Prediction Center," 2017. [Online]. Available: https://www.spc.noaa.gov/wcm/
[40] B. C. Zachry, W. J. Booth, J. R. Rhome, and T. M. Sharon, "A national view of storm surge risk and inundation," *Weather, Climate, Soc.*, vol. 7, no. 2, pp. 109–117, 2015.
[41] Federal Emergency Management Agency, "Flood Risk Database (FRD) Technical Reference," 2018. [Online]. Available: https://www.fema.gov/media-library-data/1524249062040-8a315833d69131560239507668fa779b/Flood_Risk_Database_Technical_Reference_Feb_2018.pdf
[42] U.S. Geological Survey, "USGS small-scale dataset—Federal lands of the United States shapefile," 2005. [Online]. Available: https://nationalmap.gov/small_scale/atlasftp.html
[43] U.S. Fish and Wildlife Service, "United States Fish and Wildlife Service National Cadastral Data," 2018. [Online]. Available: https://www.fws.gov/gis/data/cadastraldb/index_cadastral.html
[44] U.S. Forest Service, "National Wild and Scenic River Segments (Feature Layer)," 2018. [Online]. Available: https://www.rivers.gov/mapping-gis.php
[45] R. L. Keeney, *Siting Energy Facilities*. New York, NY, USA: Academic, 1980.
[46] United States Nuclear Regulatory Commission, "Reactor site criteria," 2012. [Online]. Available: https://www.nrc.gov/reading-rm/doc-collections/cfr/part100/full-text.html
[47] B. Bhaduri, E. Bright, P. Coleman, and M. L. Urban, "LandScan USA: A high-resolution geospatial and temporal modeling approach for population distribution and dynamics," *GeoJournal*, vol. 69, nos. 1/2, pp. 103–117, 2007.
[48] *IEEE Guide for the Transportation of Transformers and Reactors Rated 10 000 kVA or Higher*, IEEE, Piscataway, NJ, USA, 2012.
[49] American Association of State Highways and Transportation, "A Policy on Design Standards: Interstate System," 2005. [Online]. Available: http://large.stanford.edu/courses/2014/ph240/suresh2/docs/AASHTO-InterstateDesignStandards.pdf
[50] J. Butler, J. Jia, and J. Dyer, "Simulation techniques for the sensitivity analysis of multi-criteria decision models," *Eur. J. Oper. Res.*, vol. 103, pp. 531–546, 1997.
[51] A. Jimenez, S. Rios-Insua, and A. Mateos, "A decision support system for multiattribute utility evaluation based on imprecise assignments," *Decis. Support Syst.*, vol. 36, pp. 65–79, 2003.
[52] K. D. Goepel, "Implementing the analytic hierarchy process as a standard method for multi-criteria decision making in corporate enterprises—A new AHP excel template with multiple inputs," in *Proc. Int. Symp. Anal. Hierarchy Process*, Kuala Lumpur, Malaysia, 2013, pp. 1–10.
[53] M. J. de Smith, M. F. Goodchild, and P. A. Longley, *Geospatial Analysis—A Comprehensive Guide to Principles, Techniques and Software Tools*, 6th ed. Edinburgh, U.K.: Winchelsea Press, 2018.

Susan M. Kotikot received the B.Sc. degree in environmental planning and management from Kenyatta University, Nairobi, Kenya, in 2013, and the M.Sc. degree in earth system science from the University of Alabama, Huntsville, AL, USA, in 2017. She is currently working toward the Ph.D. degree with the Department of Geography, Pennsylvania State University, University Park, PA, USA.

From April 2013 to July 2014, she was a Remote Sensing Assistant with the Regional Centre for Mapping of Resources for Development. Prior to joining Penn State, she was a Post-Master's Research Associate with the Oak Ridge National Laboratory, Oak Ridge, TN, USA. Her research interests include landscape ecology, agroecosystems, climate change, remote sensing, and geographic information systems.

Bandana Kar received the B.Arch. degree from the Orissa University of Agriculture and Technology, Bhubaneswar, India in 1992, the Master of City Planning degree from the Indian Institute of Technology, Kharagpur, India, in 2001, the M.S. degree in geography from the State University of New York at Albany, Albany, NY, USA, in 2003, and the Ph.D. degree in geography from the University of South Carolina, Columbia, SC, USA, in 2008.

From 2008 to 2017, she was an Assistant Professor and then a Tenured Associate Professor with the Department of Geography and Geology, University of Southern Mississippi, Hattiesburg, MS, USA. Since 2017, she has been an R&D Staff with the Oak Ridge National Laboratory, Oak Ridge, TN, USA. She is a co-editor of the book entitled *Risk Communication and Community Resilience* (Boca Raton, FL, USA: CRC Press, 2019). She has authored or coauthored more than 35 peer-reviewed manuscripts. Her research interests include multiscale modeling, spatiotemporal analytics and geoinformatics, community and infrastructure resilience, risk and vulnerability assessment, and risk communication.

Dr. Kar was a recipient of the Emerging Scholar Award in 2019 from the American Association of Geographers' Regional Development and Planning Specialty Group. She is a Fellow of the National Science Foundation's Enabling the Next Generation of Hazards and Disasters Researchers Fellowship Program in 2009. She is an Associate Editor/Social and Behavioral Science Editor for the IEEE NATURAL HAZARDS REVIEW.

Olufemi A. Omitaomu (Senior Member, IEEE) received the B.Sc. (Hons.) degree in mechanical engineering from Lagos State University, Ojo, Nigeria, in 1995, the M.Sc. degree in mechanical engineering from the University of Lagos, Lagos, Nigeria, in 1999, and the Ph.D. degree in industrial engineering from the University of Tennessee, Knoxville, TN, USA, in 2006.

He is currently a Senior R&D Staff with the Computational Systems Modeling Group, Oak Ridge National Laboratory (ORNL), Oak Ridge, TN. He is also a Joint ORNL-UT Associate Professor with the University of Tennessee. From 1995 to 2001, he worked in the oil and gas industry as a Project Engineer. Prior to joining ORNL in October 2006, he was a Postdoctoral Fellow with McMaster University, Hamilton, ON, Canada. His research interests include data science, resilience science, cognitive systems, disaster analytics, and energy informatics.

Dr. Omitaomu is a member of the Institute for Operations Research and Management Science and the Institute for Industrial and Systems Engineers.