

Decentralized Energy and Water Networks for Community Resilience against Natural Disasters

Govind Joshi and Salman Mohagheghi

ABSTRACT

Large-scale natural disasters can severely damage the energy and water infrastructure, leading to disruption of services. In addition to raising possible health risks, lack of access to electricity and water can impede or prolong recovery from the disaster. To be resilient against such events, the electric power grid and the water distribution network must be able to continue operating with minimal impact on end-users and with constricted costs. Naturally, one approach is to reinforce the energy and water infrastructure against natural hazards. However, this may be cost-prohibitive or even infeasible. An alternative solution is to allocate sufficient localized resources such that these networks can continue operating at a decentralized scale until the main network is repaired and restored. In this paper, a solution is proposed to design a localized water and energy system that can serve a community affected by a natural disaster, with little external support. An optimization model is developed to optimally allocate resources, e.g., distributed energy resources and water storage capacity, based on the needs of the community and subject to operational constraints. Such decentralized systems can significantly improve the resilience of the energy and water networks and assist affected communities in the aftermath of disaster events.

Keywords: Distributed generation, electric microgrid, natural disasters, renewable energy resources, resilience, water micronet.

Published Online: September 5, 2022

ISSN: 2736-5506

DOI : 10.24018/ejenergy.2022.2.4.76

G. Joshi

Colorado School of Mines, Golden, CO, USA.

(e-mail: gjoshi@mines.edu)

S. Mohagheghi*

Colorado School of Mines, Golden, CO, USA.

(e-mail: smohaghe@mines.edu)

**Corresponding Author*

I. INTRODUCTION

In recent years, the changing climate and the rising global temperatures have led to an increase in the frequency and severity of natural disasters [1], [2]. Damages incurred by these events significantly impact the livelihood of the communities affected, and in addition to often long-term economic consequences, may lead to serious mental, emotional, and physical health issues [3]-[6]. Depending on its severity and scope, a natural disaster may cause serious damages to the critical infrastructure such as roads, electric power grid, water network, and telecommunication systems. Lack of access to these basic services can significantly impact the health and wellbeing of the residents in the affected regions and disrupt disaster recovery efforts. While evacuation is one option, it may not be easy (e.g., in densely populated urban areas), feasible (e.g., due to lack of access to transportation means), or desirable (e.g., for residents with financial concerns or health or disability issues) [7]. Socially vulnerable communities are in particular disproportionately affected by the social and economic impacts of natural disasters [8], [9], which can act as a vicious cycle since the subsequent poverty can further increase the population's vulnerability to future natural hazards [10], [11].

Among all essential services, access to power and water is the most critical one due to the many everyday life activities that depend on availability of electricity and clean water. In addition, these services facilitate preparedness, response, and

recovery during and in the aftermath of a disaster. While reinforcement of power and water networks is certainly an option to improve civic resilience, in many instances it may be cost-prohibitive or even infeasible. An alternative option is to introduce operational flexibility by allowing the system to operate in a decentralized fashion, for instance in the form of electric microgrids or water micronets. The electrical microgrid is a well-known concept in power distribution systems in which part of the grid can island from the main network and operate in a standalone mode upon need. Although microgrids have shown to assist with improving power quality and reducing losses, their main advantage lies in their ability to decouple from the main grid during large-scale disturbances and continue to supply the loads locally [12]-[14]. The key operational challenge however is to ensure that the microgrid can maintain its load-generation balance at all times and that it is equipped with sufficient reactive power support for voltage control. Similar to the concept of an electric microgrid, a water distribution network can be broken into smaller connected sub-systems, known as a micronet [15] with the capability to separate for standalone operation upon need. Naturally, components in the micronet need to be sized and placed strategically to ensure a smooth flow of water from source to demand points at all times. Just as microgrids need distributed energy resources (DERs) to operate, a micronet needs water sources in the form of either a storage tank/water reservoir or a wastewater treatment plant (WWTP) that treats wastewater for potable reuse. The flow

of water between the lower elevation points and the higher points are maintained by water pumps (whereas gravity is used for the reverse flow). Power for these pumps must be provided by the energy sources within the electric microgrid. Similarly, to treat wastewater, the WWTP needs electrical energy to be supplied by the microgrid.

The problem of microgrid design and operation has been studied extensively in the literature, especially when equipped with renewable energy resources and batteries [16]-[19]. In such systems, the presence of a battery is crucial to ensure that the excess generation of wind and PV can be stored for future use when the renewable energy resource is not available. Many researchers have developed solutions for computing the battery size for a microgrid, in coordination with intermittent renewable resources [20]-[26]. Design and operation of micronets can be done in a similar fashion. Solutions have been proposed in the literature for optimal operation or planning of the water distribution network, e.g., for optimal pump scheduling to minimize operation cost [27]-[29] and finding optimal sizes for tanks and pumps [30], [31]. WWTPs may also need to be utilized in order to meet the growing need for water in some communities [32], [33], especially in arid regions. Some researchers have focused on solutions to optimize the operation of the WWTP [34], [35]. While power and water networks have been traditionally studied in isolation, in recent years, the coordinated operation of the two, in the form of an energy-water nexus, has gained much attention [36], [37]. A benefit in combining the two systems into a single framework is that excess power generation (during times of low demand) can be utilized by the water network to avoid curtailing the otherwise useful energy [38]. In addition, combined operation of power and water networks allows for alleviating the volatility in the renewable energy resource as shown in [39], [40].

In this paper, the problem is viewed from a different angle, i.e., community resilience against natural disasters. It is desired to optimally allocate resources for a combined microgrid-micronet to enable its standalone operation should the main networks to which it is connected (i.e., the power grid and/or the water distribution network) become damaged and nonoperational due an external event. Sustainability is a cornerstone of the proposed approach, both from an economic perspective (i.e., lowering the cost of purchasing power or water from external sources) as well as practicality (i.e., road access to the community may have been lost due to the natural disaster). While this is intended for temporary situations, for instance until the repairs to the main grid or the water network are completed, it can be envisioned that such models may be deployed for remote communities in arid regions. The focus of the design problem addressed in this work is on determining the optimal sizes of energy resources (i.e., wind turbine, PV, and battery) and water storage tank for the community. This is done while considering the typical demand profiles for both water and energy, considered under worst-case conditions. The community battery is intended to absorb the excess generation from wind and solar resources to later use them when the energy resource is not available. Finally, while electric load shedding is considered to be a possible option for maintaining the stability of the microgrid, its use is desired to be minimized.

The rest of this paper is organized as follows. Section III

details the proposed mathematical model. Section IV presents the solution methodology adopted and the input parameters necessary to solve the model. In section V, a case study is presented and analyzed for proof-of-concept purposes. Finally, conclusions are highlighted in section VI.

II. PROBLEM FORMULATION

A. Preliminaries and Assumptions

We consider a small-scale residential community exposed to natural hazards. It is assumed that the severity of potential hazards is such that the main power grid and/or the water network from which the community is supplied may become temporarily unavailable. To improve resilience, it is desired to operate the community network as a combination of an electrical microgrid and a water micronet. The main objective in this paper is to propose an optimal resource allocation strategy for this microgrid/micronet system such that all energy and water needs are, as much as possible, met with the lowest capital investment. The daily consumption profiles for power and water are assumed known, e.g., from historical data. The options to consider for local energy needs are a community battery, a solar PV system (deployed mainly as rooftop PV), and wind turbines. Further, it is assumed that the community's local water network consists of a water storage tank and a WWTP that allows for (partial) water reuse. Further, it is assumed that no external energy resources are available (for instance, connection to the main grid). However, purchasing water from external sources is an option, although not desired. The latter assumption is made since water losses are inevitable and as a result, operating as a fully closed micronet is not practical. Utilizing technologies such as rainwater catchment systems is another option but is considered out of scope in this paper.

B. Mathematical Model

The design problem is formulated in the form of a constrained multi-objective optimization model as outlined below. The sizes of the energy and water resources are determined in such a way that the demand profiles (power and water) are met with the least amount of load curtailment. Often, to ensure a robust design capable of handling various uncertainties, the average consumption profiles are converted into worst-case conditions. We do not distinguish between the two because the choice of average versus worst-case condition does not affect the generality of the problem.

1) Objective Function

At the high level, it is desired to minimize the design cost of the system (i.e., the sizes of the energy and water resources) while ensuring an acceptable quality of service. The optimization model is formulated in the form of a multi-objective one, where the Pareto optimal solution is sought through a goal programming approach. There are six objective functions to be optimized, as outlined below.

$$\min \left\{ p^{\text{BT,cap}}, p^{\text{PV,cap}}, \sum_j u_j^{\text{WT}}, v^{\text{ST,cap}}, v^{\text{w}}, \sum_{t \in T} \left(P_t^{\text{des}} - \sum_{i \in C} p_{i,t} \right)_+ \right\} \quad (1)$$

The first two terms in (1) represent the sizes of the

community battery and the solar PV system, respectively. The third term indicates the number of fixed-capacity wind turbines installed. Unlike batteries and solar PV, where the sizes can be continuously varied, wind turbines typically come at standard sizes. Instead of varying the diameter of the turbine rotor, it is assumed here that the number of turbines is the variable to be minimized. The fourth term represents the size of the water storage tank, whereas the fifth term denotes the volume of water purchased from outside sources, which is desired to be minimized. Finally, the last term in (1) is used to ensure that, as much as possible, electric demand is met at the desired levels.

2) Constraints

The multi-objective optimization problem in (1) is solved subject to the constraints listed below.

a) Power Balance

The key operational requirement for the microgrid is the load-generation balance. Because this is a design problem, our goal is to ensure that available generation capacity exceeds electric demand, as indicated in (2). This necessitates a capability to curtail the excess wind and/or solar power (see section V for related discussion).

$$\forall t \in T: \quad (2)$$

$$\sum_j p_{j,t}^{WT} + p_t^{PV} + p_t^{BT,d} \geq \sum_{i \in C} p_{i,t} + p_t^{ww} + p_t^{BT,c}$$

Power generation from each wind turbine depends on the wind velocity and the characteristics of the rotor [see (3)]. The amount of power generation from the solar PV system depends on the installed capacity as well as the available solar irradiance. Naturally, the former would be limited by the maximum permissible amount [see (4)]. Equations (5)-(10) indicate the operational constraints of the battery. At any point in time, the battery can be either charging or discharging, but not both [see (5)]. The upper bound for charge/discharge power is limited by the installed capacity of the battery, as indicated in (6)-(7). The state-of-charge of the battery at any point in time depends on its value at the previous time step, adjusted based on the amount of charge or discharge at that point in time [see (8)], and its value must always lie within the acceptable lower and upper limits [see (9)]. Further, it has been assumed that at the first time-step, i.e., beginning of the dispatch period, the battery had been charged to its lowest permissible level, as indicated in (10).

$$\forall j, \forall t \in T: p_{j,t}^{WT} = \frac{1}{2} \frac{\alpha \cdot \rho_a \cdot A_j^{WT} \cdot w_t^3}{1,000} \cdot u_j^{WT} \quad (3)$$

$$\forall t \in T: p_t^{PV} = p^{PV,cap} \frac{\Phi_t}{\Phi_{STC}}, p^{PV,cap} \leq p^{PV,max} \quad (4)$$

$$\forall t \in T: u_t^{BT,c} + u_t^{BT,d} \leq 1 \quad (5)$$

$$\forall t \in T: 0 \leq p_t^{BT,d} \leq p^{BT,cap} u_t^{BT,d} \leq p^{BT,max} u_t^{BT,d} \quad (6)$$

$$\forall t \in T: 0 \leq p_t^{BT,c} \leq p^{BT,cap} u_t^{BT,c} \leq p^{BT,max} u_t^{BT,c} \quad (7)$$

$$\forall t \in T: \quad (8)$$

$$SOC_t = (1 - \gamma) \cdot SOC_{t-1} + \frac{p_t^{BT,c} \eta^c}{p^{BT,cap}} - \frac{p_t^{BT,d}}{\eta^d p^{BT,cap}}$$

$$\forall t \in T: SOC_{min} \leq SOC_t \leq SOC_{max} \quad (9)$$

$$SOC_o = SOC_{min} \quad (10)$$

b) Demand Curtailment

Load curtailment may need to be performed to ensure that balance between generation and demand is always met. Naturally, reducing demand beyond desired levels introduces inconvenience for the consumers, which is why its application must be regulated. The last objective function in (1) tries to achieve this at the microgrid-level. However, in addition to this, consumer equity requires that no subset of users is disproportionately affected by load curtailment. This is achieved by constraints (11)-(13). A consumer will be experiencing load shedding if the generation in system is smaller than the demand at that point in time. But the number of times during which each user experiences this must be limited [see (11)]. Moreover, the total amount of load shed experienced by each consumer during a dispatch period should not exceed a certain percentage of its overall desired demand during that same period [see (12)]. Finally, constraint (13) ensures that actual demand supplied to a consumer is not more than its desired demand. Also, when load shedding is not required for a consumer, constraint (13) prevents the formulation from incorrectly assigning more power demand than their desired level in case the total power generation in the microgrid exceeds the total system demand. In other words, constrain (13) will divert excess power to the battery system for charging purposes.

$$\forall i \in C: \sum_{t=1}^T u_{i,t} \leq N^{sh} \quad (11)$$

$$\forall i \in C: \sum_{t=1}^T (P_{i,t}^{des} - P_{i,t})_+ \leq k^{sh} \cdot \sum_{t=1}^T P_{i,t}^{des} \quad (12)$$

$$\forall i \in C, \forall t \in T: P_{i,t} = P_{i,t}^{des} \cdot (1 - u_{i,t}) \quad (13)$$

c) Water Demand

At any point in time, the total amount of water flow provided by the storage tank to the community should equal the total water demand, which is a sum of individual consumers' demands [see (14)]. Flow through pipes that are feeding users is limited by the maximum allowable rate, as indicated in (15). Without loss of generality, it is assumed that at the beginning of the dispatch period, the tank is at least filled to the level of $V^{ST,min}$. Although more water may be available if purchased from external resources [see (16)]. Equation (17) indicates the water flow balance of the tank, which depends on the starting volume, and the inflow/outflow to/from the tank at any point in time. The volume of water in the tank should never exceed its installed capacity, itself limited by the maximum permissible value [see (18)]. It is assumed that the tank is located at a higher elevation than the community, hence water can naturally flow without a need for a pump. This assumption does not affect the generality of the problem, i.e., if the tank is located at a lower elevation, power consumption of pumps that are needed to transfer water to individual houses must be incorporated into (2).

$$\forall t \in T: \sum_{i \in C} q_{i,t} = q_t^{\text{ST,out}} \quad (14)$$

$$\forall i \in C, \forall t \in T: q_{i,t} \leq q^{\text{max}} \quad (15)$$

$$v_o^{\text{ST}} = V^{\text{ST,min}} + v^{\text{w}} \quad (16)$$

$$\forall t \in T: v_t^{\text{ST}} = v_{t-1}^{\text{ST}} + q_t^{\text{ww,out}} \cdot \Delta - q_t^{\text{ST,out}} \cdot \Delta \quad (17)$$

$$\forall t \in T: V^{\text{ST,min}} \leq v_t^{\text{ST}} \leq v_t^{\text{ST,cap}} \leq V^{\text{ST,max}} \quad (18)$$

d) Wastewater Treatment Plant

It is assumed that the WWTP can treat the incoming batch of wastewater during one time-step, i.e., one hour. This has been chosen for demonstration purposes only and does not affect the generality of the problem. A certain fraction of water discharged from the consumers is collected at the WWTP to be treated, i.e., not all the water is recycled [see (19)]. Equation (20) reflects the initial volume of fluid in the WWTP. In general, the volume of wastewater depends on the amount of inflow to and outflow from the plant [see (21)] and cannot exceed its capacity, as indicated in (22). The amount of power consumed for treating the wastewater and pumping it to the reservoir is assumed to be proportional to the volume of wastewater treated, as shown in (23). Similar to before, it has been considered that the WWTP resides at a lower elevation than the storage tank.

$$\forall t \in T: q_t^{\text{ww,in}} = k^{\text{ww}} \cdot \sum_{i \in C} q_{i,t} \quad (19)$$

$$v_o^{\text{ww}} = V^{\text{ww,min}} \quad (20)$$

$$\forall t \in T: \quad (21)$$

$$v_t^{\text{ww}} = v_{t-1}^{\text{ww}} + q_t^{\text{ww,in}} \cdot \Delta - q_t^{\text{ww,out}} \cdot \Delta - q_t^{\text{ww,eff}} \cdot \Delta$$

$$\forall t \in T: V^{\text{ww,min}} \leq v_t^{\text{ww}} \leq V^{\text{ww,max}} \quad (22)$$

$$\forall t \in T: p_t^{\text{ww}} = (P^{\text{ww}} + P^{\text{pump}}) \cdot q_t^{\text{ww,out}} \cdot \Delta$$

III. MODELING APPROACH

A. Estimation of Electric Power Demand

The first step in the analysis is to identify the electric demand to be served. This will be one of the inputs to the optimization model. Typical consumption data for residential consumers was taken from [41], which contains hourly load profile for residential buildings in all Typical Meteorological Year (TMY3) locations in the United States and provides one year of hourly data that best represents median weather conditions over a multiyear period for a particular location. Load data is derived based on the Residential Energy Consumption Survey (RECS) for different building types by location. For this study, the city of Golden, CO was selected. Assuming a community consisting of 10 residential units, the individual demands are illustrated in Fig. 1.

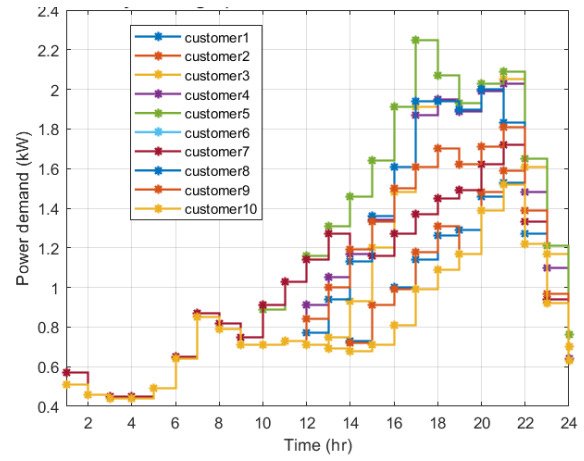


Fig. 1. Average hourly demand (kW) in the community of 10 residential consumers. Time-steps 1-24 represent the 24-hour study period.

To estimate the electric demand at the WWTP, historical data on power consumption of different electromechanical components in a typical WWTP are used. This data is taken from a WWTP located at Mines Park in Golden, CO, which has been used by the authors for research purposes. The system consists of bioreactors and membrane tanks, which together process one batch of wastewater (1.22 m³) over a two-hour period. A grinder pump is used to fill the bioreactors with incoming wastewater from the residential households. The bioreactors are equipped with electromechanical devices (air blowers and mixers) to treat the incoming wastewater (i.e., the air blower supplies oxygen to the wastewater and the mixer stirs the fluid to facilitate the necessary biochemical reactions). After being processed, the fluid is pumped via a RAS pump to the membrane tanks where small membranes filter the waste with the help of air scour blowers. Clean water is then pumped out of the membrane tanks (and the WWTP) via permeate pumps. Table I lists the nominal power consumption rate of these devices. A total of 5.55 kWh is used to treat 1.22 m³ of wastewater, i.e., 4.55 kWh per 1 m³.

TABLE I: ENERGY CONSUMPTION OF THE WWTP COMPONENTS TO TREAT ONE BATCH OF WASTEWATER (1.22 M³)

Component	Energy Consumption (kWh)
Grinder pump	0.10
Blower	1.14
Mixer	1.12
RAS pump	1.38
Air Scour Blower (ASB)	1.49
Permeate pumps	0.53
Total	5.55

B. Solar Irradiance and Wind Speed

The size of the solar PV system and the number of wind turbines needed depend on solar irradiance and wind speed data. Data for the city of Golden, CO is obtained from the National Renewable Energy Laboratory [42], [43] (Fig. 2).

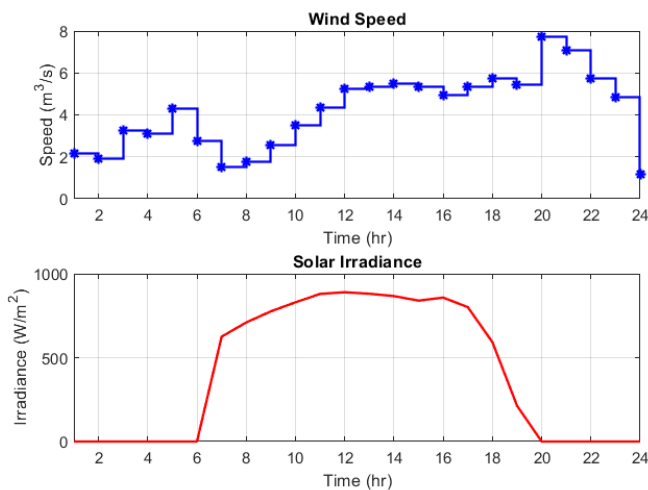


Fig. 2. Wind speed and solar irradiance data associated with the study area.

The size of the PV system is estimated based on the standard available PV panels in the market, which are rated at 250–350W capacity and measuring 1.5m×1m in size. Assuming an average total roof size of 185 m² (2,000 sq. ft.) for typical residential houses in the US [44], each residential unit can in theory make 92.5 m² (1,000 sq. ft.) of space available for installing rooftop PVs, i.e., equivalent to one roof (or one side). Considering the 1.5 m² (16 sq. ft.) area for one solar panel, this adds up to approximately 62 panels per house, producing around 18.6kW (with 300W per panel). This is equivalent to a maximum 186 kW of rooftop PV capacity for the 10 customers in the community. The maximum permissible size for the PV system is increased to 250kW for the entire community to account for houses with larger than average roof sizes and/or potential areas for a community solar garden. The size of the possible wind turbine is estimated based on the average wind speeds available in the study area. It is assumed that the community may install two types of wind turbines, i.e., turbines of size 300 kW with a 31m diameter rotor [45] and/or of size 5.5 kW with a 4.3m rotor diameter [46]. While the latter is more suitable for community generation, the latter can be installed at individual houses. Depending on the energy needs of the community, a combination of the two turbine types may be installed. Both PV and wind power generators depend on energy resources that are intermittent in nature. When there is insufficient energy available from these sources to supply the demand, a community battery may be used to ensure the power balance within the microgrid. Energy storage solutions come in different sizes. For this study, a maximum possible capacity of 200 kW is assumed for the battery.

C. Water Demand of the Community

Water demand for the households is estimated based on the hourly occupancy profile of each household and average water consumption per person. It is assumed that occupancy levels are known or can be derived from historical data available from the community. The water demand for each user is estimated to be 0.37 m³ (100 gallons) of water per day as provided by U.S. Geological Survey (USGS) [47]. The average hourly occupancy profile and water consumption levels of residential customers are provided in Fig. 3. Based on a worst-case occupancy of 3 (for each of the 10 households) and at least 0.1 m³ of water necessary to ensure

basic daily needs (per person per day, according to WHO), the minimum volume of water to be stored at the storage tank is considered to be 3 m³. Naturally, these numbers are chosen for demonstration purposes and can be changed upon need.

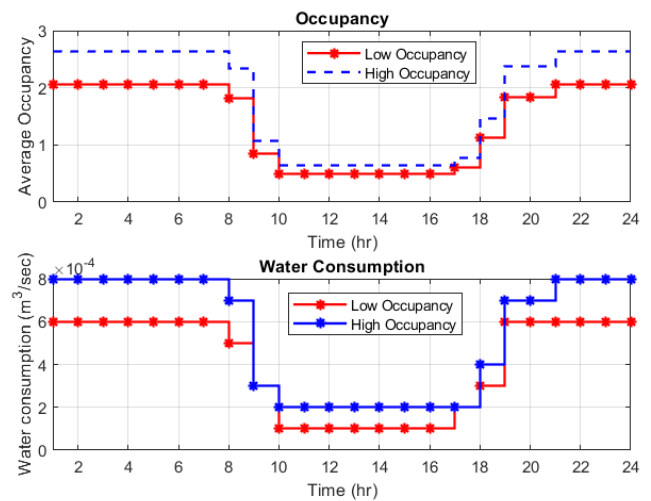


Fig. 3. Hourly average occupancy and water demand for community households.

The size of the water pump required at the WWTP is estimated as in (24) [48]:

$$p_t = \frac{\rho \cdot g \cdot q_t^{ww,out} \cdot H}{\eta} \quad (24)$$

It is assumed here that the water distribution system is already in place and able to supply an average flow rate of 0.0007 m³/s per house (or approximately 11 gallons per minute (GPM), which is estimated based on the assumption of a maximum of 2.2 GPM for 5 faucets in the house located in bathrooms, kitchen, shower, and laundry area as per the US EPA's standard [49]) at 41 m water head (approximately 60 pound per square inch (PSI) or 414 kPa water pressure). Hence, the total head from WWTP to storage tank needs to be at least 41 m. With these values, a pump system with a power rating of 4.022 kW (5.39 hp) is chosen. This implies that the pump would consume 0.21 kWh per unit volume of water lift at that pressure. This number is close to the 0.19 kWh/m³ requirement of water pumping provided in [50].

D. Multi-Objective Solution Methodology

The optimization model proposed in this paper is a multi-objective one and is solved using the Chebyshev Goal Programming (CGP) approach. The problem can be expressed as follows, where objectives O_1 through O_6 are the size of the community battery, size of the solar PV system, number of wind turbines, size of the community water storage tank, amount of water to be purchased from outside sources, and amount of load shed, respectively [see (1) for details].

$$\min \left\{ \lambda + \sum_{q=1}^6 \varepsilon \frac{O_q}{G_q} \right\} \quad (25)$$

Subject to:

$$\forall q: \frac{S_q}{G_q} \leq \lambda \quad (26)$$

$$O_q - s_q \leq G_q \quad (27)$$

$$\forall q: s_q \geq 0 \quad (28)$$

In these equations s_q 's are deficiency variables that allow objectives to deviate from the user defined goals (targets) G_q [see (27)]. However, the amount of the deviation must be minimized, as indicated in (26). Variable λ is an auxiliary decision variable that provides an upper bound on the normalized deficiency variables. The objective in this combined model is to simultaneously optimize all objective functions so that their respective deviations from their target values are minimized.

IV. CASE STUDY

A. Simulation Results

In this section, objective function (25) is solved subject to constraints (2)-(23) and (26)-(28) for a community of 10 residential units, with electricity and water demand profiles as in Figs. 1 and 3. The proposed optimization model is solved using General Algebraic Modeling System (GAMS) software using an Intel® Core™ i7-8750H CPU @ 2.5GHz–2.21GHz desktop computer. The optimization model was run multiple times with an average convergence time of approximately 28 minutes, median convergence time of 28 minutes, and standard deviation of 1.16 minutes.

To solve the CGP model, the following approach is adopted: Each objective function O_q is first solved in isolation, i.e., ignoring other objectives, to find its true optimum value. These values (subject to a slight deterioration) are then used as the goals (targets) to be met in the multi-objective setting. In cases such as this study, where the objectives are contradictory to one another, the goals are normally never met.

As relates to the design of the wind energy system, two options are considered: (a) using a maximum of two large wind turbines, each of capacity 300 kW or (b) using a maximum of one large wind turbine of capacity 300 kW and up to 40 small wind turbines of capacity 5.5 kW each.

1) Case Study 1: Two Large Wind Turbines

Table II lists the results of solving the single objective (SO) optimization models. In each case, only one objective function is optimized, while the other functions are free to assume any value. It appears that in this example based on the corresponding numerical data, wind and solar PV can generate sufficient power to meet the demand during most time-steps, which explains why there is little need for energy storage. Regardless of what objective function is being optimized, the number of wind turbines to be installed always remains at 2. This is because without the wind power, the energy needs of the community cannot be met since the battery is not sufficiently charged in the early morning when there is no solar power irradiance available either. Naturally, since the problem is solved over time, the worst-case scenario (e.g., hours of especially low generation or especially high demand) would always dominate the design solution.

The single objective optima, i.e., cells highlighted in Table II, are then used as the basis to determine the goal (target) values for the multi-objective model. As is common for goal programming models with contradictory objectives, each SO

optimum is slightly deteriorated (typically 10%, except for the integer values) before it is set as the goal (target). Table III summarizes the results. It can be seen that all objective functions worsen in the multi-objective (MO) setting compared to the single objective one. This is expected due to the conflicting nature of the objectives.

TABLE II: SINGLE OBJECTIVE (SO) OPTIMIZATION RESULTS IN CASE STUDY 1

Min	O ₁ : Battery size (kW)	O ₂ : PV size (kW)	O ₃ : Number of turbines deployed	O ₄ : Water storage tank capacity (m ³)	O ₅ : Water purchased (m ³)	O ₆ : Total load shed (kW)	Number of load shed instances
O ₁	6.84	250	2	200	197	5.53	10
O ₂	10.60	19.5	2	200	197	9.76	10
O ₃	10.07	250	2	200	197	5.03	10
O ₄	10.64	250	2	144.32	141.32	5.36	10
O ₅	10.71	250	2	200	141.32	5.36	10
O ₆	10.60	20.1	2	200	197	3.37	7

TABLE III: SO AND MULTI-OBJECTIVE (MO) VALUES IN CASE STUDY 1

Objective Function	SO	Goal (Target)	MO
	Optima	Values	Optima
O ₁ : Battery size (kW)	6.84	7.52	9.24
O ₂ : PV size (kW)	19.45	21.40	25.54
O ₃ : Number of wind turbines deployed	2.00	3	2.00
O ₄ : Water storage tank capacity (m ³)	144.32	155.75	193.86
O ₅ : Water purchased (m ³)	141.32	155.45	190.86
O ₆ : Total load shed (kW)	3.37	3.71	4.13

The design problem converges to a solution in which both wind turbines are installed, in addition to a solar PV capacity of 25.54 kW and a battery capacity of 9.24 kW. Fig. 4 illustrates the total amount of power available from different energy resources as well as the overall generation and demand. There is slight excess generation at some hours, which are either curtailed (e.g., during time-steps 12-15) or used to charge the battery (e.g., during time-step 20). Alternatively, the curtailed power could have been stored in the battery, however, that would have required a larger size battery which is not desired. Fig. 5 illustrates the charging of the battery at time-step 20 to its rated capacity to then discharge at time-step 24.

Fig. 6 illustrates the hourly balance between generation and demand, as well as the instances of load shedding. There is an increased power demand for the WWTP during time-steps 10 to 22 as it is treating the water and pumping it into the storage tank. The decrease in WWTP level during time steps 10-18 and 20-23 and the increase in water level in the storage tank during these times denotes the pump operation to supply the water needs of the community (Fig. 7). There is little or no power consumption during other time-steps by the WWTP because the tank supplies clean water to the community via gravity. Because of this, the size of the tank must be large enough to store sufficient water for a longer period of time. As the community consumes water for daily activities, the volume of water in the storage tank and the WWTP undergo variations. As per the solution in Table 3, a storage tank of size 193.37 m³ (approximately 51,082 gallons) is required to meet the water demand in the community over a 24-hour period. In addition, the community needs to purchase 190.37 m³ of water each day in order to adjust the balance.

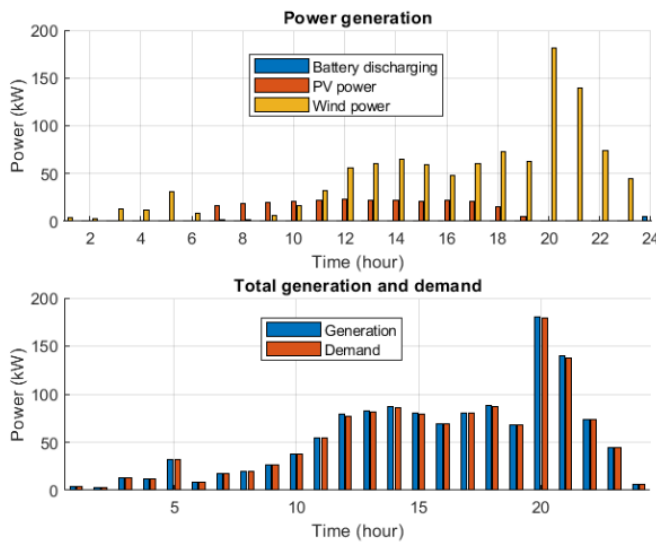


Fig. 4. Hourly generation (top) and load-generation balance (bottom) for case study 1.

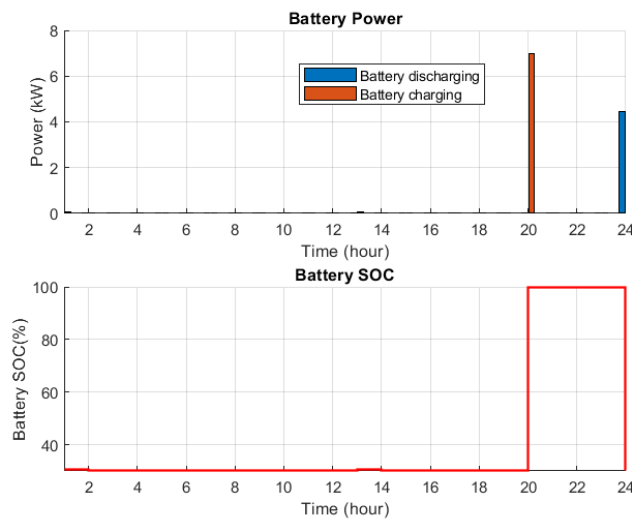


Fig. 5. Battery power (top) and SOC (bottom) for case study 1.

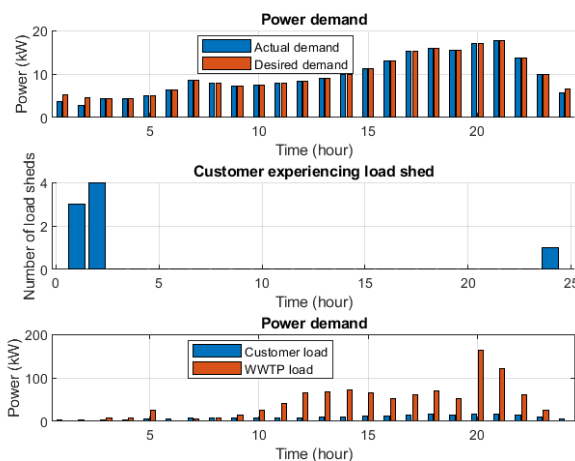


Fig. 6. Power balance (top), instances of load curtailment (middle) and total demand (bottom) for case study 1.

As per the design criteria, each customer may experience load shedding for only 1 time-step throughout the study period (or only for 1 hour a day). This indicates a maximum of 10 load shedding instances. As shown in Fig. 6, three customers experience load shedding during time-step 1, four

during time-step 2, and one during time-step 24, for a total of 8 load shed instances. These were necessary to maintain balance between load and generation.

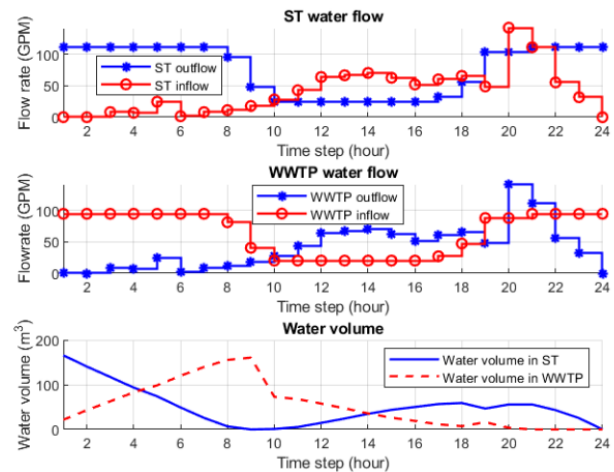


Fig. 7. Hourly water flow in and out of the storage tank (top) and the WWTP (middle), and the variations in volume of water in the storage tank and the WWTP (bottom) for case study 1.

2) Case Study 2: One Large Wind Turbine and Up to 40 Small Wind Turbines

In this case study, it is considered that that wind energy system may consist of up to one large turbine (300 kW) and up to 40 small scale turbines (5.5 kW), i.e., a maximum of 4 small turbines installed at each residential unit. Other resource capacities, e.g., solar PV size and battery size, are similar to case study 1. Table 4 presents the results of the single objective problems. The overall solution is presented in Table 5, where a combination of one large wind turbine, 35 small turbines, a battery storage system of 9.40 kW, and a solar PV system of size 42.41 kW are needed to supply the energy needs. Because the total theoretical capacity available from this combination of turbines is less than that of case study 1, it can be seen that the required sizes of the solar PV and battery slightly increase.

TABLE IV: SINGLE OBJECTIVE (SO) OPTIMIZATION RESULTS IN CASE STUDY 2

Minimize	O ₁ : Battery size (kW)	O ₂ : PV size (kW)	O ₃ : Number of turbines deployed*	O ₄ : Water storage tank capacity (m ³)	O ₅ : Water purchased (m ³)	O ₆ : Total load loss (kW)	Number of loads shed
O ₁	9.36	250	40	200	197	5.21	10
O ₂	10.72	32.3	40	200	197	6.65	10
O ₃	10.86	250	27	200	197	4.91	10
O ₄	10.72	250	40	146.1	143.13	5.05	10
O ₅	10.72	250	40	200	143.13	5.05	10
O ₆	10.76	32.6	40	200	197	4.3	9

*The large wind turbine is always selected to be deployed.

B. Discussion

In general, the choice of energy resources and their corresponding sizes depends on both the demand profile (electricity and water) as well as the profiles for wind and solar energy. To be robust against data uncertainties, worst-case scenarios can be considered, i.e., overestimating demand while underestimating wind/irradiance. This poses a tradeoff between the cost of deployment and the level of reliability

achieved within the microgrid-micronet system. Given the nature of the problem, i.e., resilience during natural disasters, it may be more appropriate to consider average profiles for demand and generation, as opposed to the worst-case scenario, in order to arrive at a more economical solution. However, it is also possible to consider the latter to achieve higher reliability levels. Such an over-designed system is likely to have excess generation during normal operation, which can be sold back to the utility in order to compensate for the higher initial investment.

TABLE V: SO AND MULTI-OBJECTIVE (MO) VALUES IN CASE STUDY 2

Objective Function	SO Optima	Goal (Target) Values	MO Optima
O ₁ : Battery size (kW)	9.36	10.30	9.40
O ₂ : PV size (kW)	32.29	35.52	42.41
O ₃ : Number of wind turbines deployed ON	27	30	36*
O ₄ : Water storage tank capacity (m ³)	146.13	158.04	190.98
O ₅ : Water purchased (m ³)	143.13	157.44	187.98
O ₆ : Total load shed (kW)	4.34	4.774	5.16

*The large wind turbine is always selected to be deployed

In the current study, only active power was considered and power losses in the system were ignored. This is a reasonable assumption for a small-scale residential microgrid with high power-factor inductive loads, which is the focus of this paper. However, in special situations where the load power factor may be low, reactive power constraints may also need to be included and the problem would need to be solved for the apparent powers provided by energy resources, not just their active powers. Of course, this would require the energy resources to be equipped with power electronics converters that enable reactive power control. Another operational aspect to consider when utilizing wind and solar resources is whether the output power can be controlled (as was the case in this paper). Less expensive wind turbines and rooftop solar PV units typically operate at the maximum power point tracking (MPPT) mode, which means any energy available from wind or the Sun will be converted to electricity and injected into the grid. On the other hand, with generator control, excess generation can be curtailed upon need, albeit at the expense of utilizing more complicated and costlier power electronics circuitry. The choice between power regulation and MPPT modes of operation has direct implications on the size of the battery. With MPPT, excess generation cannot be curtailed, which means it must be stored somewhere. This requires a larger size battery, which is more expensive. However, the instances of load shedding may go down since more power is now available in the battery. In the proposed formulation, MPPT mode of operation can be easily implemented by changing the inequality constraint in (2) to an equality one, which requires the sum of generation at each point in time to be equal to demand (including battery charging).

The financial aspects of system design were intentionally left out of the current study. This is because system procurement and deployment costs vary from one region to another, and no impartial conclusions can be made. However, if needed, this can be easily incorporated into the problem formulation by adding another objective function, e.g., a cost function consisting of the cost of PV and battery per kW

installed and the cost of the wind system as a function of the number of turbines installed. The granular focus on individual households (e.g., using rooftop PV or small-scale wind turbines) makes the solution practical for any residential neighborhood in which consumers are willing and able to make the initial investment (perhaps with the help of federal and state incentives). The only exception to this is the large-scale wind turbine, which is at the commercial level and not appropriate for residential customers. However, this could be installed at the WWTP.

V. CONCLUSIONS

The changing climate has led to an increase in the frequency and severity of weather-related natural disasters. These events can lead to widespread damages to the critical infrastructure of the affected areas, including the electric power grid and the water distribution network. Access to electricity and water is essential especially in the aftermath of natural disasters and during recovery efforts. One solution to achieve resilience is to design power and water networks as a system of subsystems, in which each subsystem (electric microgrid and/or water micronet) can operate in a standalone mode with little or no support from the outside world, at least until repairs to the centralized networks are completed. Devising one such approach was the focus of this paper.

An optimization model was proposed to allocate the optimum types and sizes of energy and water resources for a hybrid microgrid-micronet spanning a residential neighborhood. It was assumed that the neighborhood is equipped with a wastewater treatment plant to provide potable water reuse. Further, wind turbines, solar PV, and battery energy storage were considered as options to supply the electricity needs of the system. The problem was formulated as a multi-objective mixed-integer nonlinear programming model (MINLP), in which it was desired to find the smallest size energy and water resources to be able to meet the daily local demand. Naturally, the various objectives will be conflicting at times, which is why goal programming was used as the solution methodology to ensure that a Pareto optimal solution is achieved. It was shown through a case study that using average consumption profiles as well as wind and solar irradiance profiles, it is possible to find optimum sizes for energy resources and water storage tank such that the electricity and water needs of the community are met with the least amount of disruption. Such decentralized designs can be implemented for regions that are prone to severe natural hazards. Although the initial investment may be significant, it can be justified by the net savings over time as well as the improved resilience during disaster events.

NOMENCLATURE

A. Indices and Sets

C	Set of consumers in the community, which are viewed as both power and water demand points
<i>i</i>	Index used for consumers
<i>j</i>	Index used for wind turbines
<i>q</i>	Index used for objective functions within the multi-objective framework
<i>t</i>	Index used for time

B. Parameters and Input Data

A_j^{WT}	Area swept by the rotor of wind turbine j (m^2)
G_q	Goal (target) value for objective function q in the multi-objective framework
k^{sh}	Maximum allowable percentage of consumer load that can be shed during a dispatch period, assumed to be 10% in this study
k^{ww}	Portion of consumed water that will be discharged as waste, i.e., the ratio of water inflow to a household to water outflow from it to the sewer system. Assumed to be 0.85
N^{sh}	Maximum allowable number of times during a dispatch period that a consumer may experience load shedding. Naturally: $N^{sh} < T$. Assumed to be 1.0 in this study
$P^{BT, max}$	Maximum permissible generation capacity of the community battery (kW)
$P^{PV, max}$	Maximum permissible generation capacity of the solar PV panel (kW)
P^{ww}	Power consumed by wastewater treatment plant (WWTP) for treating $1m^3$ of wastewater (kW/m^3)
P^{pump}	Power consumed to pump $1 m^3$ of treated wastewater from the WWTP to the community water storage tank (kW/m^3)
$P_{i,t}^{des}$	Desired active power consumption of consumer i at time t (kW)
P_t^{des}	Desired active power consumption of the entire community at time t (kW)
$q_{i,t}$	Water consumption rate of consumer i at time t (m^3/s)
q^{max}	Maximum water flow rate through pipes. This is limited by the designed flow rate of the water network (m^3/s). Assumed to be 0.007
SOC^{min}	Minimum allowable state-of-charge (SOC) of the community battery (%), considered to be 30% in this study
SOC^{max}	Maximum allowable SOC of the community battery (%), considered to be 100% in this study
T	Time horizon of the study period (hours, minutes, etc.)
$V^{ST,min}$	Minimum permissible volume of water in the community ST (m^3). This can be determined based on the minimum amount of water considered to be necessary to ensure basic daily needs for the community residents. The amount is estimated by the World Health Organization (WHO) to be between 50–100 liters (0.05 – $0.1 m^3$) per person per day
$V^{ST,max}$	Capacity of community water storage tank (m^3)
$V^{ww,max}$	Maximum permissible volume of wastewater in the WWTP (m^3), assumed to be 50 in this study
$V^{ww,min}$	Minimum permissible volume of wastewater in the WWTP (m^3), assumed to be 0
w_t	Wind speed at the wind turbine location at time t (m/s). Assumed to be the same for all turbines.
α	Power coefficient constant for wind turbines, assumed to be 0.425
γ	Self-discharge rate of the community battery (p.u), assumed to be 0.0025
Δ	Duration of a single time-step of analysis (seconds, minutes, etc.)
η^c/η^d	Charge/discharge efficiency of the community battery (dimensionless), assumed to be 0.8

ρ_a	Air density (kg/m^3), assumed to be 1.22
Φ_t	Incident solar irradiance at the community solar PV panel at time t (W/m^2)
Φ^{STC}	Incident solar irradiance at the standard test conditions (STC) (W/m^2)

C. Variables

λ	Auxiliary decision variable used in the multi-objective optimization framework, whose role is to provide an upper bound for the deficiency variables
O_q	Objective function q in the multi-objective framework
$p^{BT, cap}$	Installed capacity of the battery (kW)
$p_{i,t}$	Power consumed by consumer i at time t (kW)
$p_t^{BT,c}$	Power provided to charge the community battery at time t (kW)
$p_t^{BT,d}$	Power discharged by the community battery at time t (kW)
$p^{PV, cap}$	Installed capacity of the solar PV panel (kW)
p_t^{PV}	Power provided by the community solar PV panel at time t (kW)
$p_{j,t}^{WT}$	Power provided by wind turbine j at time t (kW)
p_t^{ww}	Power consumed by the WWTP at time t (kW)
$q_t^{ST,out}$	Outgoing flow rate from the community water storage tank at time t (m^3/s)
$q_t^{ww,eff}$	Effluent flow rate from the WWTP at time t (m^3/s). This is the amount of untreated wastewater, which is discharged to make sure that the tank does not go over capacity
$q_t^{ww,in}$	Incoming flow rate to the WWTP at time t (m^3/s)
$q_t^{ww,out}$	Outgoing flow rate (associated with treated wastewater) from the WWTP at time t (m^3/s)
SOC_t	State-of-charge of battery at time t (%)
s_q	Deficiency variable associated with objective q in the multi-objective framework
$u_{i,t}$	Binary variable indicating if consumer i is experiencing load shedding at time t (=1: load shed, 0: desired demand met)
u_j^{WT}	Binary variable indicating if wind turbine j is deployed (=1: turbine is installed, 0: not installed)
$u_t^{BT,c}$	Binary variable indicating if the community battery is being charged at time t (= 1: charged, 0: not charged)
$u_t^{BT,d}$	Binary variable indicating if the community battery is being discharged at time t (= 1: discharged, 0: not discharged)
v_t^{ST}	Volume of water at the community water storage tank at time t (m^3)
$v^{ST, cap}$	Installed capacity of the community water storage tank (m^3)
v^w	Volume of water received from external resources (m^3). Without loss of generality, it is assumed that the supply is provided only at the beginning of the dispatch period
v_t^{ww}	Volume of wastewater at WWTP at time t (m^3)

FUNDING

This work was in part supported by the National Science Foundation under grant 1632227.

CONFLICT OF INTEREST

Authors declare that they do not have any conflict of interest.

REFERENCES

- [1] Anderson J, Bausch C. Climate change and natural disasters: Scientific evidence of a possible relation between recent natural disasters and climate change. [Internet]. 2006 [cited 2021 Nov 15]. Available from: https://www.europarl.europa.eu/meetdocs/2004_2009/documents/dv/ieep_cc_natural_disasters/ieep_cc_natural_disasters_en.pdf.
- [2] Banholzer S, Kossin J, Donner S. *Reducing disaster: Early warning systems for climate change*, Springer, 2014, pp. 21–49.
- [3] Halverson JB, Rabenhorst T. Hurricane Sandy: The science and impacts of a superstorm. *Weatherwise*, 2013; 66(2):14–23.
- [4] Vigdor J. The economic aftermath of Hurricane Katrina. *J. Econ. Perspect.* 2008; 22(4):135–154.
- [5] Satake K, Atwater BF. Long-term perspectives on giant earthquakes and tsunamis at subduction zones,” *Annu. Rev. Earth Planet. Sci.* 2007; 35:349–374.
- [6] Ohnishi T. The disaster at Japan’s Fukushima-Daiichi nuclear power plant after the March 11, 2011 earthquake and tsunami, and the resulting spread of radioisotope contamination. *Radiat. Res.* 2012; 177(1):1–14.
- [7] Thomas DSK, Phillips BD, Fothergill A, Blinn-Pike L. *Social vulnerability to disasters*. CRC Press; 2009.
- [8] Veenema TG, Thornton CP, Lavin RP, Bender AK, Seal S, and Corley A. Climate change-related water disasters’ impact on population health. *J. Nurs. Scholarsh.* 2017; 49(6):625–634.
- [9] Benevolenza MA, DeRigne L. The impact of climate change and natural disasters on vulnerable populations: A systematic review of literature. *J. Hum. Behav. Soc. Environ.* 2019; 29(2):266–281.
- [10] Fordham M, Lovekamp WE, Thomas DSK, Phillips BD. Understanding social vulnerability. *Soc. vulnerability to disasters*. 2013; 2:1–29.
- [11] Rodríguez H, Russell CN. Understanding disasters: vulnerability, sustainable development, and resiliency. *Public Sociol. Read.* 2006; 193–211.
- [12] Quashie M, Joos G. A methodology to optimize benefits of microgrids. *Proceedings of the 2013 IEEE power & energy society general meeting*, pp. 1–5, Vancouver, BC, Canada, July 2013.
- [13] Venkataramanan G, Marnay C. A larger role for microgrids. *IEEE Power Energy Mag.* 2008; 6(3):78–82.
- [14] Choobineh M, Mohagheghi S. Emergency electric service restoration in the aftermath of a natural disaster,” *Proceedings of the 2015 IEEE Global Humanitarian Technology Conference*, pp. 183–190, Seattle, WA, USA, October 2015.
- [15] Falco GJ, Webb WR. Water microgrids: The future of water infrastructure resilience. *Procedia Eng.* 2015; 118:50–57.
- [16] Chen SX, Gooi HB, Wang M. Sizing of energy storage for microgrids. *IEEE Trans. Smart Grid.* 2011; 3(1):142–151.
- [17] Kahrobaee S, Asgarpour S, Qiao W. Optimum sizing of distributed generation and storage capacity in smart households. *IEEE Trans. Smart Grid.* 2013; 4(4):1791–1801.
- [18] Atia R, Yamada N. Sizing and analysis of renewable energy and battery systems in residential microgrids. *IEEE Trans. Smart Grid.* 2016; 7(3):1204–1213.
- [19] Rodríguez-Gallegos CD, Yang D, Gandhi O, Bieri M, Reindl T, Panda SK. A multi-objective and robust optimization approach for sizing and placement of PV and batteries in off-grid systems fully operated by diesel generators: An Indonesian case study. *Energy.* 2018; 160:410–429.
- [20] Alharbi H, Bhattacharya K. Optimal sizing of battery energy storage systems for microgrids. *Proceedings of the 2014 IEEE Electrical Power and Energy Conference*, pp. 275–280, Calgary, AB, Canada, November 2014.
- [21] Bludszuweit H, Domínguez-Navarro JA. A probabilistic method for energy storage sizing based on wind power forecast uncertainty. *IEEE Trans. Power Syst.* 2010; 26(3):1651–1658.
- [22] Hartmann B, Dán A. Methodologies for storage size determination for the integration of wind power. *IEEE Trans. Sustain. Energy.* 2013; 5(1):182–189.
- [23] Bahramirad S, Reder W, Khodaei A. Reliability-constrained optimal sizing of energy storage system in a microgrid. *IEEE Trans. Smart Grid.* 2012; 3(4):2056–2062.
- [24] Cao B, Dong W, Lv Z, Gu Y, Singh S, Kumar P. Hybrid microgrid many-objective sizing optimization with fuzzy decision. *IEEE Trans. Fuzzy Syst.* 2020; 28(11):2702–2710.
- [25] Jordehi AR. Optimisation of demand response in electric power systems, a review,” *Renew. Sust. Energy Rev.* 2019; 103:308–319.
- [26] Denholm P, Mai T. Timescales of energy storage needed for reducing renewable energy curtailment. *Renew. Energy.* 2019; 130:388–399.
- [27] Fooladivanda D, Taylor JA. Energy-optimal pump scheduling and water flow. *IEEE Trans. Control Netw. Syst.* 2017; 5(3):1016–1026.
- [28] Jowitt PW, Germanopoulos G. Optimal pump scheduling in water-supply networks. *J. Water Resour. Plan. Manag.* 1992; 118(4):406–422.
- [29] Moosavian SA. *Optimal design of water distribution networks under uncertainty*. PhD Thesis. University of British Columbia; 2018.
- [30] Batchabani E, Fuamba M. Optimal tank design in water distribution networks: review of literature and perspectives. *J. water Resour. Plan. Manag.* 2014; 140(2):136–145.
- [31] Cunha M, Marques J. A new multiobjective simulated annealing algorithm—MOSA-GR: Application to the optimal design of water distribution networks. *Water Resour. Res.* 2020; 56(3):1–29.
- [32] Yuksel E, Eroglu V, Sarikaya HZ, Koyuncu I. Current and future strategies for water and wastewater management of Istanbul City. *Environ. Manage.* 2004; 33(2):186–195.
- [33] Yerri S, Piratla KR. Decentralized water reuse planning: Evaluation of life cycle costs and benefits. *Resour. Conserv. Recycl.* 2019; 141:339–346.
- [34] Kendrick DA, Rao HS, Wells CH. Optimal operation of a system of waste water treatment facilities. *Proceedings of the 1970 IEEE Symposium on Adaptive Processes Decision and Control*, Austin, TX, USA, December 1970.
- [35] Hakanen J, Sahlstedt K, Miettinen K. Wastewater treatment plant design and operation under multiple conflicting objective functions. *Environ. Model. Softw.* 2013; 46:240–249.
- [36] Zohrabian A, Plata SL, Kim DM, Childress AE, Sanders KT. Leveraging the water-energy nexus to derive benefits for the electric grid through demand-side management in the water supply and wastewater sectors. *Wiley Interdiscip. Rev. Water.* 2021; 8(3):e1510.
- [37] da Silveira APP, Mata-Lima H. Energy audit in water supply systems: a proposal of integrated approach towards energy efficiency. *Water Policy.* 2020; 22(6):1126–1141.
- [38] Fooladivanda D, Domínguez-García AD, Sauer PW. Utilization of water supply networks for harvesting renewable energy. *IEEE Trans. Control Netw. Syst.* 2018; 6(2):763–774.
- [39] Wang F, Xu J, Liu L, Yin G, Wang J, Yan J. Optimal design and operation of hybrid renewable energy system for drinking water treatment. *Energy.* 2021; 219:119673.
- [40] Moazeni F, Khazaei J. Optimal operation of water-energy microgrids; a mixed integer linear programming formulation. *J. Clean. Prod.* 2020; 275:122776.
- [41] Office of Energy Efficiency & Renewable Energy. *Commercial and residential hourly load profiles for all TMY3 locations in the United States* [Internet]. 2014 [cited 2021 November 15]. Available from: <https://data.openepi.org/submissions/153>.
- [42] NSRDB. *National solar radiation data base* [Internet]. 2005 [cited 2021 November 15]. Available from: https://rredc.nrel.gov/solar/old_data/nsrdb/1991-2005/tmy3/.
- [43] National Renewable Energy Lab. *Wind integration national dataset toolkit* [Internet]. 2021 [cited 2021 Nov 15]. Available from: <https://www.nrel.gov/grid/wind-toolkit.html>.
- [44] U. S. C. Bureau. *Characteristics of new housing*, [Internet]. 2021 [cited 2021 Nov 15]. Available from: <https://www.census.gov/construction/chars/>.
- [45] Wind Energy Market Intelligence. *The wind power* [Internet]. 2018 [cited 2021 Nov 15]. Available from: www.thewindpower.net/turbine_en_348_nordtank_ntk300-31.php.
- [46] Ryse Energy. *Ryse Energy 5 kW wind turbines* [Internet]. 2021 [cited 2021 Nov 15]. Available from: <https://www.ryse.energy/5kw-wind-turbines/>.
- [47] USGS. *Water science school* [Internet]. 2020 [cited 2021 November 15]. Available from: <https://www.usgs.gov/special-topic/water-science-school/science>.
- [48] Milnes M. *The mathematics of pumping water* [Internet]. 2017 [cited 2021 Nov 15]. Available from: <http://www.raeng.org.uk/publications/other/17-pumping-water>.
- [49] Commission California Energy. California code of regulations title 20 [Internet]. 2016 [cited 2021 November 15]. Available from: <https://www.epa.gov/sites/production/files/2017-10/documents/ws-commercialbuildings-waterscore-residential-kitchen-laundry-guide.pdf>.
- [50] Peacock B. *Energy and cost required to lift or pressurize water* [Internet]. 1996 [cited 2021 November 15]. Available from: <https://cetulare.ucanr.edu/files/82040.pdf>.