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Evaluate the capacity of electricity-driven water facilities in small communities as virtual energy storage

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ABSTRACT

In small communities, such as small islands, campuses of universities/industrial parks/lab facilities, and remote villages/cities, the Water-Energy Nexus (WEN) operators generally need to purchase electricity from the power grid to meet a portion of their power demand. The WEN of these communities creates new opportunities of providing virtual energy storage (VES) and virtual power plant (VPP) services to the power grid by properly controlling their electricity-driven water facilities (EDWF). This paper investigates the capacity of EDWFs in small communities as VES and VPP. Small communities in four different types of areas, e.g., island, desert, urban, and rural, are studied based on their geographical specifications, to evaluate and compare the capabilities of their WENs as VES and VPP respectively. WENs with high penetration of photovoltaic resources are considered, for which battery energy storage systems (BESS) are needed. An optimization approach of operating the EDWFs as VES is proposed to reduce the required size of BESSs. The state-of-the-art convex technologies are adopted to reduce the computational burden of the developed optimization models which are large-scale mixed-integer nonlinear programming problems. Besides, the WEN of small communities is modeled as a VPP to provide spinning reserve energy for the power grid in emergency conditions. This paper also describes how the EDWFs can be controlled to serve as a virtual system and provides substantial benefits for the small communities. Numerical results validate that it is economically beneficial to operate the WENs of small communities as VES or VPP for renewable energy management of power grids.

1. Introduction

In recent years, researchers found that it is beneficial to operate the power distribution network (PDN) and water distribution system (WDS) as a whole which is known as the Water-Energy Nexus (WEN) [1–4]. On one hand, some challenges of balancing the demand and supply in PDNs can be mitigated by coordinating the PDN with the WDS. On the other hand, it can help the water utilities reduce the energy costs for water treatment and supply. In small communities, such as small islands, campuses of universities, industrial parks, and lab facilities, and remote villages, the entire WEN is most likely owned and controlled by a single entity that purchases electricity from the power grid to meet a portion of the power demand. Some islands, such as Bahrain and Singapore, have to purchase electricity to meet part of their power demand due to their increasing power demand [5,6]. Naxos island which is a Greek island was connected to the mainland's power grid in 2020 to provide power for a portion of its demand [7,8]. Campuses that own water utilities and energy services purchase some portion of their power demand from other companies. For example, the WEN in the University of Central Florida (UCF) campus controls and maintains its water and power system and supplies the majority of all domestic water to the main campus [9]. A portion of electricity consumption of the UCF main campus is from Duke Energy [10].

Reducing the total operational cost of the WENs is one of the important tasks for the owners of these small communities. Most of the water facilities in WDSs, such as pumps and desalination plants, rely on electrical energy and can operate flexibly. For instance, the desalination plants consume 10% to 20% of total energy consumption in Saudi Arabia [11], and the electricity consumed by water systems accounts for 4% to 16% of total electricity consumption in the United States [12]. Substantial research efforts have been invested to reduce the energy consumption of water systems, where the optimal pump scheduling (OPS) is one of the developed approaches [2–4,13,14]. The co-optimization of power and water networks is investigated in recent years [15–18]. The flexibility of electric-driven water facilities (EDWF) could create new opportunities for the WENs of small communities to

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Nomenclature

Parameters

η	Constant efficiency of the pump.
$\underline{\mu}, \overline{\mu}$	Lower and upper energy rate of the BESS.
A_j	Heated area.
A_n^{T}	Water tank area at node n.
C_0	Initial salt concentration of feed water.
C_{ib}	Energy capacity cost of BESS.
C_{iv}	Power conversion system cost of BESS.
C_{o}	BESS operational cost for 1 kWh.
COP_i	Coefficient of performance of cooling system at bus i.
D, L	Diameter and length of the pipe.
$d_{n,t}$	Water demand of node n at time t.
e^i	Required energy for production 1m^3 water with desalination plant at bus i.
$E_{i,0}^{\mathrm{B}}$	Initial energy of the BESS at bus i.
f_s	Surface resistance coefficient of water pipe.
g	Gravitational acceleration.
G_{tot}	Total conduction heat transmission coefficient.
h_n	Elevation of node n.
N_b	Total number of bus.
$P_{i,t}^{\mathrm{Cool}}$	Power demand of cooling system at bus i and time t.
$P_{i,t}^{\mathrm{L}}, Q_{i,t}^{\mathrm{L}}$	Active and reactive power load at bus i and time t.
$P_{i,t}^{\mathrm{PV}}, Q_{i,t}^{\mathrm{PV}}$	Active and reactive power generation by PV system at bus i and time t.
P_{SR}	Capacity of spinning reserve.
Pr_{SR}	Spinning reserve price.
Pr_{E}	Energy price.
q_{floor}	Heat transmission to ground.
r_{ij}	Resistance of line ij.
r_i^{BESS}	Loss coefficient related to the BES at bus i.
$r_i^{\mathrm{w}}, r_i^{\mathrm{ww}}$	Required energy for production 1m^3 water with water treatment plant and waste water treatment plant at bus i.
$R^{\mathrm{Des}}, R^{\mathrm{m}}$	Recovery ratio, membrane resistance for the desalination.
R_{nm}^{w}	Head loss coefficient of pipe nm.
$\overline{S_{ij}}$	Maximum apparent power of the line between bus i and j.
T_s, T_o	Set point and outdoor temperature.
x_{ij}	Reactance of line ij.
z_{ij}	Sum of square of resistance and reactance of line ij.

Variables

α	Binary variable related to pump status.
β_i^{b}	Binary variable related to location of BESS.
C_{buy}	Cost of purchasing electricity from the power grid.
C_{ins}	Installation Cost of BESS.
C_{inv}	Investment Cost of BESS.
C_{opr}	Operational Cost of BESS.
$DE_{i,t}$	Desalination specific energy consumption at bus i and time t.
E_i^{BES}	Energy rating of the BESS at bus i.
E^{BESS}	Energy capacity of BESS.
$f_{nm,t}$	Water flow of pipe nm at time t.
$F_{n,t}^{\mathrm{R}}$	Water flow inject from the water source at node n and time t.
$F_{n,t}^{\mathrm{RDes}}$	Water production of desalination at time t and node n.
$F_{n,t}^{\mathrm{Rw}}, F_{n,t}^{\mathrm{Rww}}$	Water production of water treatment and wastewater treatment at time t and node n.
$F_{n,t}^{\mathrm{T}}$	Water flow of tank at node n and time t.
$\mathcal{I}_{ij,t}$	Square of current in line ij at time t.
j_t	Water flux for Desalination at time t.
$L_{i,t}^{\mathrm{BES}}$	Active power loss of the BES at bus i and time t.
P_i^{BES}	Power rating of the BES at bus i.
P^{BESS}	Power capacity of BESS.
$P_{i,t}^{\mathrm{B}}$	Active power charge/discharge by BES at bus i and time t.
$P_{ij,t}, Q_{ij,t}$	Active and reactive power in line ij at time t.
$P_{i,t}^{\mathrm{Des}}$	Power demand of desalination at bus i and time t.
$P_{i,t}^{\mathrm{G}}, Q_{i,t}^{\mathrm{G}}$	Active and reactive power generation at bus i and time t.
$P_{i,t}^{\mathrm{Pump}}$	Power demand of pump at bus i and time t.
$P_{i,t}^{\mathrm{w}}, P_{i,t}^{\mathrm{ww}}$	Power demand of water treatment and waste water treatment at bus i and time t.
$\mathcal{V}_{i,t}$	Square of voltage at bus i and time t.
$V_{n,t}^{\mathrm{T}}$	Water tank volume at node n and time t.
$y_{n,t}$	Water head at node n and time t.
$y_{nm,t}^{\mathrm{G}}$	Head gains imposed by the pump in pipe nm at time t.

operate as a virtual system, such as virtual energy storage (VES) [19] and virtual power plant (VPP) to the power grid. The owners of small communities can control the EDWFs as virtual systems to achieve minimum operational cost and energy efficiency benefits.

Although renewable energy resources are critical for energy sustainability, their intermittent nature and uncertainty [20,21] incur several problems to power system operation, for example, the problems that result from a power imbalance. The energy storage system, such as battery energy storage system (BESS), can decrease the effects of renewable power generation fluctuation and prevent the rising of voltage in the distribution network when the penetration of renewable energy resources is high [22]. However, the BESS is still too expensive to be practical. This paper will explore to control EDWFs as VES for renewable energy management such that the required BESS can be reduced. Considering energy storage in power system optimization generally results in large-scale, computationally-intractable problems. In this paper, we will extend a convex hull model [23] of BESS to a planning model of finding the optimal size and location of BESS to evaluate the capacity of the WDSs as VES.

Demand Response (DR) plays a significant role in reserve energy and frequency response, especially during peak time and system contingency [24–26]. Balancing supply and demand is one of the significant challenges in power system operation that can be addressed through DR services. WDSs can provide DR services to the power grid to address the balance between demand and supply and frequency response in a power network [15,27,28]. Fast response capability of WDSs provides a good opportunity to work as a VPP for participating in the spinning reserve (SR) market. For situations, like contingencies, that need to call on SR occur infrequently (typically once or twice a month) [29], the WDSs have the potential to serve as VPP with an acceptable change in their operation. SR system should be capable of ramping within ten minutes and running for at least two hours based on the definition from the California Independent System Operator (CAISO). The CAISO needs SR to control system frequency stability during emergency conditions or when the actual renewable power is drastically different from the forecasted one [30]. To sum up, we believe that the WEN operator in a small community can control the WDS operation to serve as a VPP for the power grid.

To compare the capacity of a small community WEN in providing SR and work as a VPP with its capacity as a VES, all power demand in this community should be considered. The authors of [27,28] investigate the participation of WDS in reserve energy through DR by using OPS. However, they only consider OPS and do not consider other power loads and EDWFs such as desalination. Although the authors investigate the desalination plant and pump in [31], they assume that a WDS network can participate in a regulation market without any change in their operation. While the WDS must store enough water in the water tanks to satisfy the water demand over the course of the DR.

Water resource availability is a crucial problem for water utilities in many areas [32]. The world faces water scarcity due to the growth of the human population and climate changes, such that, by 2025, more than 1.8 billion people will suffer from water scarcity [33]. Only 2.5% of total water in the world is freshwater, and just 0.014% of all resources are available for humans [34]. A solution for water scarcity is to improve the water usage efficiency via recycling which relies heavily on electric energy. Moreover, the availability of freshwater resources is diverse in different areas based on their locations and geographical specifications. Consequently, small communities have different WDS based on this situation. Some regions, such as Russia and the north of America, have substantial freshwater resources. However, in other areas, such as the Middle East and North Africa (MENA) and most of the islands, people suffer from freshwater scarcity [35,36]. To cope with water scarcity, the small communities have to use alternative water supply methods, such as wastewater treatment plants and desalination plants, which are electricity-consuming. Indeed, the EDWFs of small communities demand different amounts of power according to location and geographical specifications. As a result, the WDSs of the small communities in the various areas have different capacities to work as VPPs and VESs.

To further explore the potential opportunities of WEN in small communities, this paper proposes two different roles for a WDS in a WEN as controllable loads to minimize the total cost of the WEN. First, the WDS is operated as a VES to decrease the size of BESS in the PDN of a small community. Second, the WEN operator controls the EDWFs of the WDS to participate in a SR market as a VPP. We investigate WDSs of four types of small communities in different geographical areas to figure out the prioritization of WDS capacity as a VPP or as a VES. The PDN is modeled by an AC power flow model integrated with BESSs, high penetration of renewable energy, cooling system, water treatment, wastewater treatment, water desalination, and water pumps. The Darcy–Weisbach equation is applied to model the water pipe network [37,38]. Besides, The ON/OFF status of pumps and the location of BESSs are represented by integer variables. As a result, the mathematical model of a WEN is mixed-integer nonlinear.

The coordination between the PDN and WDS are twofold: first, the WDS is operated as a VES; and secondly, the WDS serves as a VPP. The main contributions of this paper can be summarized as follow: This paper proposes that the entire WEN of a small community is owned by a single entity and can be controlled as a VES and a VPP to the power grid. The WDSs of small communities in four different types of geographical areas are defined to evaluate their capacity as VES and VPP. The capability of the WDSs as VES is investigated in a WEN of the small communities with high penetration of photovoltaic (PV) and integrated BESS. A convex hull model of BESS from [23] is extended to have both planning and operation modes. Moreover, the participation of WDSs as a VPP in a SR market is studied in order to decrease the total operational cost of the WEN in the small communities. Finally, the capability of different types of WDSs is evaluated to figure out the WDS of which area has more benefits for the small community to coordinate as a VES, and which one is better to operate as a VPP to provide SR for the power grid that selling electricity to the small community.

The rest of this paper is organized as follows: four WDSs in the small communities for four types of geographical areas are introduced in Section 2. The problem formulation is explained in Section 3. Section 4 discusses the assumptions to relax the non-convex constraints. In Section 5, different case studies are provided according to the WDS types, and power sector scenarios, while the conclusion is drawn in Section 6.

2. Electricity-driven water facilities in small communities

Surface water and groundwater are two conventional water resources. Wastewater treatment, desalination, and imported water can serve as a water resource as a mitigation of water scarcity. For example, imported water and desalination satisfy about 50% and 25% of Singapore's water demand, respectively [39], and Arizona uses treated wastewater for agriculture [40]. The availability of these different types of water resources is diverse in various areas. The small communities, such as small islands, campuses of universities/industrial parks/lab facilities, and remote villages/cities, have to consider different WDS based on their location and geographical specifications. This paper considers different WDSs of WENs for four types of representative geographical areas based on the literature review to reach general conclusions: urban area, rural area, desert area near the sea, and island area. Fig. 1 sketches these WDSs for the different types of geographical areas.

2.1. Urban area

Generally, urban areas use surface water and groundwater as water resources. Surface water must be filtered and disinfected and needs more extensive treatment [41,42] since it contains more pollutants than groundwater [43]. Although cities began to install wastewater treatment systems in the late nineteenth century and municipal wastewater treatment plants are now very common [44], the water produced by wastewater treatment plants is still not good enough as a water supply resource in this area. Based on the literature review, we consider a representative WDS for urban areas that contains two water resources: surface water and groundwater. Therefore, the paper supposes that the WDS of this small community consists of a water treatment plant and a water pump (as shown in Fig. 1(a)). These EDWFs need power for the treatment of water and for pumping the water from a reservoir to various parts of the community.

2.2. Rural area

Rural areas are different in water demand and water supply from the urban areas. Agricultural water demand, as major water demand for groundwater in the world, is more common in rural areas [45]. Besides, decentralized wastewater systems are used in small communities in

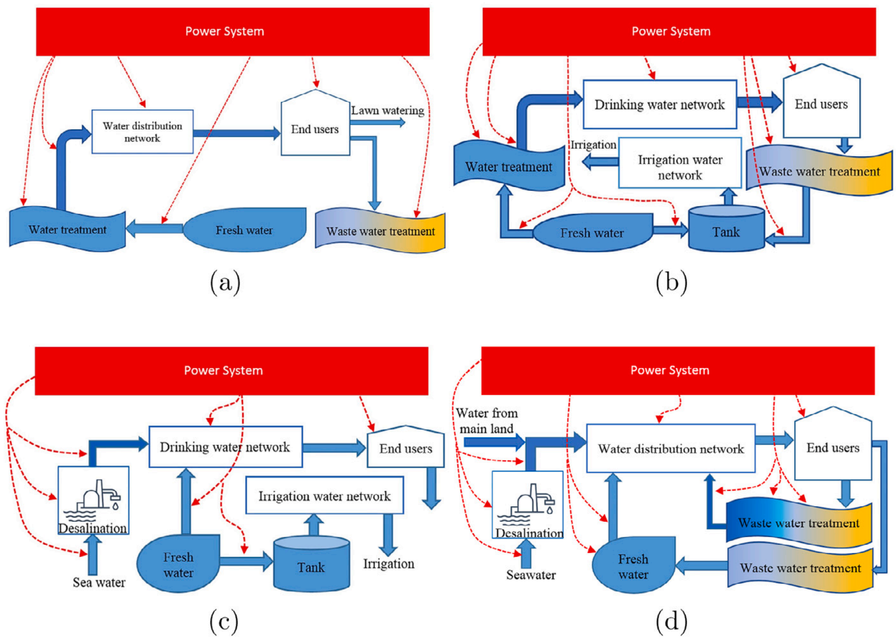

Fig. 1. WDS for the small communities in different areas: (a) Urban area; (b) Rural area; (c) Desert area near the sea; (d) Island area.

rural areas [44]. Based on the literature review, this paper considers a representative WDS for rural areas with three water resources: groundwater, surface water, and wastewater treatment plants. A water treatment plant, a wastewater treatment plant, and a water pump are considered as EDWFs for the rural area (as shown in Fig. 1(b)).

2.3. Desert area near the sea

Areas of physical water scarcity cover much of the world, such as the MENA countries [46]. Small communities in these areas need a unique WDS due to seawater accessibility and freshwater scarcity (especially surface water). The Persian Gulf countries have installed desalination plants to address their water resources shortage [47,48]. Two water resources have been considered in a representative WDS for this type of area based on the literature review: groundwater and desalination plants. Therefore, the EDWFs consist of a desalination plant and a water pump (as shown in Fig. 1(c)).

2.4. Island area

More than 10% of the world's population live in islands that suffer from water scarcity, not only for water demand growth regarding increasing the population and tourism but also because of climate change [32,49]. These areas have to install the desalination and wastewater treatment plants as a novel fresh water resource [32], while a portion of the total water demand can come from the mainland [49]. For example, the most meaningful water supply method for Singapore is imported water from other places [50]. A different type of WDS is applied for the island areas to cover their difference from other types of WDSs. In a representative WDS in islands, three water resources are considered based on the literature review: groundwater or water from a mainland, desalination plants, and wastewater treatment plants. A desalination plant, a wastewater treatment plant, and a water pump are considered as EDWFs for the island area (as shown in Fig. 1(d)).

3. Problem formulation

This section describes the formulation of a WEN in small communities, such as small islands, campuses of universities/industrial parks/lab facilities, and remote villages/cities. The WEN operator purchases power from the power utilities to meet a portion of the communities' power demand. Fig. 2 shows the schematic of a typical WEN. The blue section of Fig. 2 shows a WDS that its EDWFs will be considered as a VES or a VPP for the power grid in this paper. The WDS consists of a pipe network, pump, water treatment, wastewater treatment, and desalination. The PDN, which is a distribution network integrated with high penetration of renewable energy and BESS, is displayed in the green section. The connections between these two networks are shown with green dash lines and would be changed based on the geographical location of the community. The black dash lines show the interconnection between the PDN of the community and the power grids. The detailed model of this system is discussed in the following subsections.

3.1. Power distribution network model

This section introduces the formulation of the power network, which consists of PV, power loads, and BESS. There are several formulations for modeling the power flow in the distribution system. One of the popular linear approximations of power flow equations is the DC power flow model. Since the high r/x-ratio of the feeders, the DC power flow model is not accurate for modeling the distribution networks. The conventional rectangular and polar AC power flow models are the others method for formulating the power network. They are highly nonconvex and incur significant complexity in computation. Therefore, these models are not good options for the formulation of the PDN. The $Distflow$ model is based on the bus variables and the branch variables and is suitable for modeling both active and reactive power flows in PDNs. This model is preferred in radial networks due to the angle constraints can be neglected. Many researchers use this exact and simple model for formulating the power distribution optimization problem. We use this model in our study to achieve the exact modeling of the power distribution system and avoid any unnecessarily high nonconvexity. The $Distflow$ model is represented with constraint (1a) to (1f). Please refer to [51] for more details about the $Distflow$ model.

$$\mathcal{V}_{i,t} - \mathcal{V}_{j,t} = 2(r_{ij}P_{ij,t} + x_{ij}Q_{ij,t}) - z_{ij}\mathcal{I}_{ij,t}, \tag{1a}$$

$$\sum_{k}(P_{ki,t}) + r_{ij}\mathcal{I}_{ij,t} - P_{ij,t} = P^{\mathrm{G}}_{i,t} - P^{\mathrm{L}}_{i,t} + P^{\mathrm{PV}}_{i,t} - P^{\mathrm{B}}_{i,t}, \tag{1b}$$

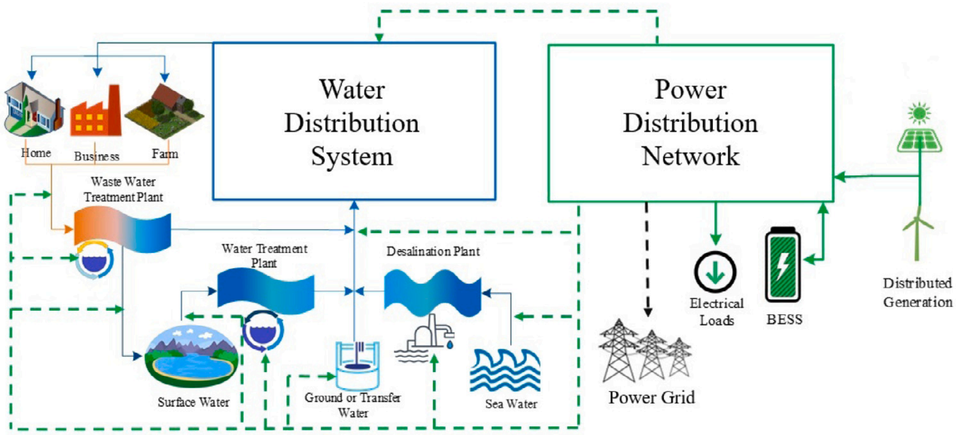

Fig. 2. WEN for a small community connected to a power grid.

$$\sum_k (Q_{ki,t}) + x_{ij}\mathcal{I}_{ij,t} - Q_{ij,t} = Q^{\mathrm{G}}_{i,t} - Q^{\mathrm{L}}_{i,t} + Q^{\mathrm{PV}}_{i,t}, \tag{1c}$$

$$P^2_{ij,t} + Q^2_{ij,t} = \mathcal{V}_{i,t}\mathcal{I}_{ij,t}, \tag{1d}$$

$$P^2_{ij,t} + Q^2_{ij,t} \leq \overline{S_{ij}}^2, \tag{1e}$$

$$\underline{P^{\mathrm{G}}_i}, \underline{Q^{\mathrm{G}}_i}, \underline{\mathcal{V}_i}, \underline{\mathcal{I}_{ij}} \leq P^{\mathrm{G}}_{i,t}, Q^{\mathrm{G}}_{i,t}, \mathcal{V}_{i,t}, \mathcal{I}_{ij,t} \leq \overline{P^{\mathrm{G}}_i}, \overline{Q^{\mathrm{G}}_i}, \overline{\mathcal{V}_i}, \overline{\mathcal{I}_{ij}}. \tag{1f}$$

3.2. Battery energy storage system model

This section discusses the BESS model. A linear BESS model has been developed for power grids integrated with renewable energy [52–54]. Nevertheless, this model is simple and cannot accurately capture the characteristics of BESS in distribution networks. A nonlinear model for BESS is proposed in some related Refs. [55,56]. This formulation is nonconvex and hard to solve. A nonlinear quadratic BESS model and its convex hull relaxation have been developed in [23] for the operation mode of BESS, while the size and location of BESS are known. In this paper, we extend this convex hull BESS model for planning purposes. Although a BESS can provide reactive power, we focus on evaluating the active capacity of EDWFs in reducing the kWh of BESS size. The modified quadratic BESS planning model is given as follow:

$$\underline{\mu} E^{\mathrm{BES}}_i \leq E^{\mathrm{B}}_{i,0} - \Delta t \sum_{t=0}^{t} (P^{\mathrm{B}}_{i,t} + L^{\mathrm{BES}}_{i,t}) \leq \overline{\mu} E^{\mathrm{BES}}_i, \tag{2a}$$

$$r^{\mathrm{BESS}}_i (P^{\mathrm{B}}_{i,t})^2 = L^{\mathrm{BES}}_{i,t}\mathcal{V}_{i,t}, \tag{2b}$$

$$-P^{\mathrm{BES}}_i \leq P^{\mathrm{B}}_{i,t} \leq P^{\mathrm{BES}}_i, \tag{2c}$$

$$E^{\mathrm{BES}}_i \leq M\beta^{\mathrm{b}}_i, \tag{2d}$$

$$P^{\mathrm{BES}}_i \leq M\beta^{\mathrm{b}}_i. \tag{2e}$$

Eq. (2a) represents the state of charge constraint. Constraint (2b) shows the power losses in a BESS. The limitation of power charging/discharging of BESS is shown in (2c). Besides, a binary variable β^{b}_i regarding the location of BESS in the PDN is added to the formulation by constraints (2d) and (2e) to determine the optimal location of BESS. M is a big value in constraints (2d) and (2e).

3.3. Water distribution system model

The mathematical model of WDSs, which consists of mass flow conservation law, pipe flow model, and pumps, is given as follow [15,57]:

$$\sum_m f_{nm,t} = F^{\mathrm{R}}_{n,t} - d_{n,t} + F^{\mathrm{T}}_{n,t}, \tag{3a}$$

$$y_{n,t} - y_{m,t} + h_n - h_m = R^{\mathrm{w}}_{nm} sgn(f_{nm,t}) f^2_{nm,t}, \tag{3b}$$

$$\begin{cases} y_{n,t} - y_{m,t} + h_n - h_m + y^{\mathrm{G}}_{nm,t} = R^{\mathrm{w}}_{nm} f^2_{nm,t}, & \text{if pump is ON} \\ f_{nm,t} = 0, & \text{if pump is OFF.} \end{cases} \tag{3c}$$

$$\underline{F^{\mathrm{R}}_n}, \underline{F^{\mathrm{T}}_n}, \underline{V^{\mathrm{T}}_n} \leq F^{\mathrm{R}}_{n,t}, F^{\mathrm{T}}_{n,t}, V^{\mathrm{T}}_{n,t} \leq \overline{F^{\mathrm{R}}_n}, \overline{F^{\mathrm{T}}_n}, \overline{V^{\mathrm{T}}_n}, \tag{3d}$$

$$\underline{y_n}, \underline{f_{nm}} \leq y_{n,t}, f_{nm,t}, \leq \overline{y_n}, \overline{f_{nm}}, \tag{3e}$$

$$V^{\mathrm{T}}_{n,t+1} = V^{\mathrm{T}}_{n,t} + F^{\mathrm{T}}_{n,t}, \tag{3f}$$

$$y^{\mathrm{T}}_{n,t+1} = y^{\mathrm{T}}_{n,t} + \frac{F^{\mathrm{T}}_{n,t}}{A^{\mathrm{T}}_n}. \tag{3g}$$

3.4. Models of electricity-driven water facilities

In this section, the EDWFs are modeled. These loads are connected to both of water and power network and are controllable loads.

3.4.1. Pumps model

In this paper, we only consider fixed-speed pumps for simplicity and a pump is considered a special pipe with a head gain imposed which can be modeled by a quadratic function of the water flow across the pump, i.e. $y = af^2 + bf + c$ [14,58]. Since $af^2 \ll bf + c$, the nonlinear af^2 can be neglected and $y = bf + c$ [59]:

$$\eta P^{\mathrm{pump}}_{i,t} = 2.725 \times f_{nm,t} y^{\mathrm{G}}_{nm,t} = 2.725 \times (b(f_{nm,t})^2 + c f_{nm,t}). \tag{4}$$

3.4.2. Desalination plants model

We consider the reverse osmosis type of desalination in our modeling. The energy demand for the desalination plant, which is a quadratic function of water flow, is given as follow [60,61]:

$$DE = 2.05 \times 10^{-5} \frac{2 - R^{\mathrm{Des}}}{2(1 - R^{\mathrm{Des}})} C_0 + 2.78 \times 10^{-7} R^{\mathrm{m}} j, \tag{5a}$$

$$P^{\mathrm{Des}}_{i,t} = DE_{i,t} F^{\mathrm{RDes}}_{n,t} = DE_{i,t} R^{\mathrm{Des}} j_t. \tag{5b}$$

Constraint (5a) shows the specific energy consumption for a reverse osmosis desalination plant. Constraint (5b) represents the power demand for the desalination plant.

3.4.3. Water treatment and waste water treatment plants model

The energy consumption per unit of water treatment and wastewater treatment is less than that of a desalination plant. For example, the energy ratio needed to treat 1 m^3 of wastewater ranges from 1.00 to 1.51 kWh [62], and municipal wastewater treatment in China and the USA are 1.11 to 1.39 and 0.64 to 1 kWh/m^3, respectively [63]. Eqs. (6a) and (6b) are the linearized formulation of these facilities [64,65].

$$P^{\mathrm{w}}_{i,t} = r^{\mathrm{w}}_i F^{\mathrm{Rw}}_{n,t}, \tag{6a}$$

$$P^{\mathrm{ww}}_{i,t} = r^{\mathrm{ww}}_i F^{\mathrm{Rww}}_{n,t}. \tag{6b}$$

3.5. Water tank level for spinning reserve

In the reserve energy application, the WEN operator needs to meet the forecasted water demand of the small community when the WEN is providing DR service to the grid. Hence, a constraint regarding water tank level is considered to ensure the reliability of WDS when EDWFs work as a VPP [27]:

$$V_{\mathrm{T}}^{n,t} \geq V_{\mathrm{T}}^{n,t*}, \tag{7}$$

where $V_T^{n,t*}$ is the minimum value of stored water in this tank at time t guaranteeing the reliable operation of WDS in the course of participating in SR.

3.6. Objective function for virtual energy storage

EDWFs can serve as a VES in the PDN with high penetration of renewable energy resources to reduce the size of BESS for renewable energy management. The objective function of the optimization model is to minimize the total cost of providing energy for a small community in order to meet both the water and electricity demands. The total operational cost consists of four sections: the investment cost related to the batteries and converters, the installation cost, such as the cost of ground for the BESS installation, the cost of purchasing electricity from the power grid, and the BESS operational cost. The objective function is given (8a) to (8g):

$$\mathrm{Cost} = C_{\mathrm{inv}} + C_{\mathrm{ins}}\left(\sum_{i=1}^{N_b} \beta_i^{\mathrm{b}}\right) + C_{\mathrm{opr}} + C_{\mathrm{buy}}, \tag{8a}$$

$$C_{\mathrm{inv}} = \frac{E^{\mathrm{BESS}} \times C_{\mathrm{ib}}}{365 \times N} + \frac{P^{\mathrm{BESS}} \times C_{\mathrm{iv}}}{365 \times N}, \tag{8b}$$

$$C_{\mathrm{ins}} = \frac{\text{Total Installation Cost}}{365 \times N}, \tag{8c}$$

$$C_{\mathrm{opr}} = \sum_{i=1}^{N_b} \sum_{t=1}^{24} C_{\mathrm{o}} \times P_{i,t}^{\mathrm{B}}, \tag{8d}$$

$$C_{\mathrm{buy}} = \sum_{i=1}^{N_b} \sum_{t=1}^{24} P_{i,t}^{\mathrm{G}} \times Pr_{\mathrm{E}}(t), \tag{8e}$$

$$E^{\mathrm{BESS}} = \sum_{i=1}^{N_b} E_i^{\mathrm{BES}}, \tag{8f}$$

$$P^{\mathrm{BESS}} = \sum_{i=1}^{N_b} P_i^{\mathrm{BES}}. \tag{8g}$$

Eq. (8a) shows the total operational cost. Eqs. (8b) and (8c) represent the daily investment and installation costs which depend on the project year (N). The installation cost depends on the number of BESS. Therefore, a binary variable β_i^{b} regarding the location of BESS in the PDN is added to the installation cost term in the objective function. Eq. (8d) shows the operational cost of BESS and Eq. (8e) represents the cost of purchasing electricity from the power grid. Eqs. (8f) and (8g) show the total capacity of energy and power that are installed in the WEN".

Eqs. (1)–(6) are the constraints of the optimization model that considers EDWFs as VESs.

3.7. Objective function for virtual power plant

Most of EDWFs have fast response [66,67], and this capability provides an opportunity for small community WEN to work as a VPP for participating in the SR market and decrease the total operational cost. The WEN operator can manage the EDWFs with some minor changes to work as a VPP for the power grid. For this purpose, the following objective function is used to minimize the total operational cost of the small community WEN:

$$\mathrm{Cost} = \sum_{t=0}^{24} (P_{\mathrm{SR}}(t)) \times (Pr_{\mathrm{E}}(t) - Pr_{\mathrm{SR}}(t)). \tag{9}$$

Eqs. (1), (3)–(7) are the constraints of the optimization model that considers EDWFs as VPPs.

4. Convex relaxation

WDSs and PDNs are large and complex systems. It is computationally intractable to solve mixed-integer nonlinear programming problems for these systems. In this section, we utilize the computational effective convex optimization technology to reduce the computational burden by convexifying the nonconvex WDS and PDN models.

4.1. Power and water distribution network constraints

We use the convex hull relaxation for relaxing constraints (1d), (3b), and (3) [59]. Constraint (1d) can be relaxed into the following convex hull relaxation:

$$P_{ij,t}^2 + Q_{ij,t}^2 \leq \mathcal{V}_{i,t}\mathcal{I}_{ij,t}, \tag{10a}$$

$$\underline{\mathcal{V}_i}\,\overline{\mathcal{V}_i}\,\mathcal{I}_{ij,t} + \overline{S_{ij}}^2\,\mathcal{V}_{i,t} \leq \overline{S_{ij}}^2\left(\underline{\mathcal{V}_i} + \overline{\mathcal{V}_i}\right). \tag{10b}$$

The nonconvex constraint (3b) contains sign functions, can be relaxed into convex hull relaxation model:

$$y_{n,t} - y_{m,t} + h_n - h_m \begin{cases} \leq (2\sqrt{2}-2)R_{mn}^{\mathrm{w}}\overline{f_{mn}}f_{mn,t} + (3-2\sqrt{2})R_{mn}^{\mathrm{w}}\overline{f_{mn}}^2 \\ \geq (2\sqrt{2}-2)R_{mn}^{\mathrm{w}}\underline{f_{mn}}f_{mn,t} - (3-2\sqrt{2})R_{mn}^{\mathrm{w}}\underline{f_{mn}}^2 \\ \geq 2R_{mn}^{\mathrm{w}}\overline{f_{mn}}f_{mn,t} - R_{mn}^{\mathrm{w}}\overline{f_{mn}}^2 \\ \leq 2R_{mn}^{\mathrm{w}}\underline{f_{mn}}f_{mn,t} + R_{mn}^{\mathrm{w}}\underline{f_{mn}}^2 \end{cases} \tag{11}$$

To eliminate the logic proposition of constraint (3), we can use the big-M technique:

$$y_{n,t} - y_{m,t} + h_n - h_m + y_{nm,t}^{\mathrm{G}} - R_{mn}^{\mathrm{w}} f_{mn,t}^2 \geq M(\alpha - 1), \tag{12a}$$

$$y_{n,t} - y_{m,t} + h_n - h_m + y_{nm,t}^{\mathrm{G}} - R_{mn}^{\mathrm{w}}\overline{f_{mn}}f_{mn,t} \leq M(1 - \alpha), \tag{12b}$$

$$f_{mn,t} \leq \overline{f_{mn}}\alpha, \tag{12c}$$

Eq. (12c) guarantees that the water flow in the pump will be zero when pump status is OFF.

4.2. Battery energy storage system constraints

Constraint (2b) in the BESS model is nonconvex. A convex hull relaxation has been developed in [23] for the operation mode of BESS. We have considered energy rating and power rating as variables to expand this model to the planning model. Eq. (13) is the convex relaxation model for constraint (2b):

$$r_i^{\mathrm{BESS}}(P_{i,t}^{\mathrm{B}})^2 \leq L_{i,t}^{\mathrm{BES}}\mathcal{V}_{i,t}. \tag{13}$$

4.3. Pump constraints

Constraint (4) is a quadratic equation which is nonconvex. It can be relaxed as shown in (14). Please refer to [15] for more details.

$$\eta P_{i,t}^{\mathrm{pump}} \geq 2.725 \times (b(f_{n,t})^2 + c f_{n,t}) \tag{14a}$$

$$\eta P_{i,t}^{\mathrm{pump}} \leq 2.725 \times (b\overline{f_n} + c) f_{n,t} \tag{14b}$$

4.4. Desalination constraints

The power demand of a desalination plant is a quadratic function of water flow. The authors of [61] provide a method to linearize this power demand. They use piece-wise linearization for modeling a desalination plant. In this paper, this method is executed to relax the quadratic equation of a water desalination plant. Eqs. (15a) and (15b) are used to convexify constraints (5a) to (5b) [61]:

$$P_{i,t}^{\mathrm{Des}} = e^i \times F_{n,t}^{\mathrm{RDes}} \tag{15a}$$

Table 1
WEN loads location and types of WDSs information.

Water resource/type of WDS		Urban	Rural	Desert	Island
Ground or transfer water	Water Supply Percentage (%)	30	60	50	50
	Bus No. in Power System	–	–	–	–
Water treatment	Water Supply Percentage (%)	70	30	0	0
	Bus No. in Power System	652	652	–	–
Waste water treatment	Water Supply Percentage (%)	0	10	0	20
	Bus No. in Power System	–	646	–	646
Desalination plant	Water Supply Percentage (%)	0	0	50	30
	Bus No. in Power System	–	–	611	611

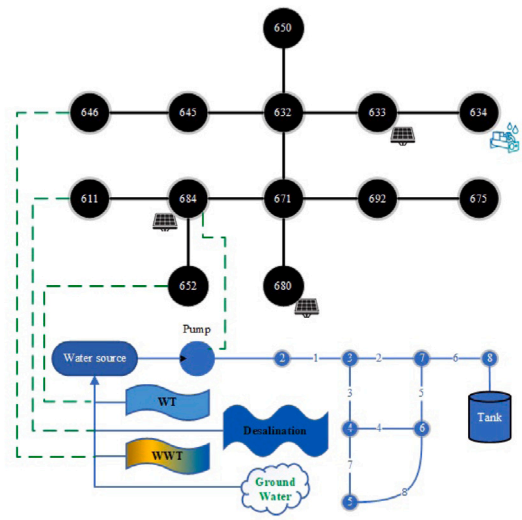

Fig. 3. The topology of the test WEN for a small community.

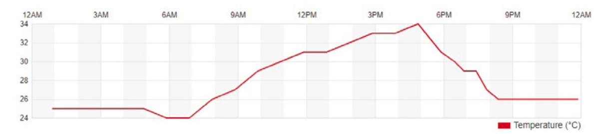

Fig. 4. 24-hour temperature of Orlando on July 28, 2019.

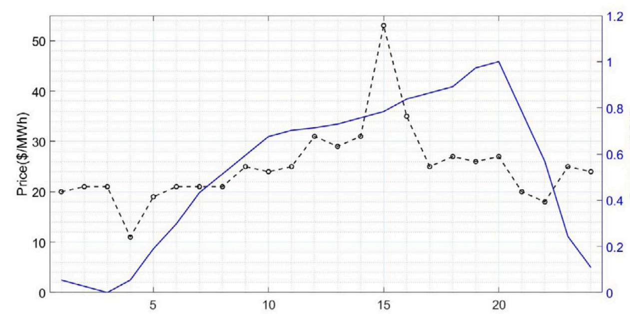

Fig. 5. Load curve of electrical loads and hourly energy price.

$$e^i = \begin{cases} e_1^i, & 0 \le F_{n,t}^{\mathrm{RDes}} \le 0.25 \times \overline{F_n^{\mathrm{RDes}}} \\ e_2^i, & 0.25 \times \overline{F_n^{\mathrm{RDes}}} \le F_{n,t}^{\mathrm{RDes}} \le 0.5 \times \overline{F_n^{\mathrm{RDes}}} \\ e_3^i, & 0.5 \times \overline{F_n^{\mathrm{RDes}}} \le F_{n,t}^{\mathrm{RDes}} \le 0.75 \times \overline{F_n^{\mathrm{RDes}}} \\ e_4^i, & 0.75 \times \overline{F_n^{\mathrm{RDes}}} \le F_{n,t}^{\mathrm{RDes}} \le \overline{F_n^{\mathrm{RDes}}} \end{cases} \tag{15b}$$

5. Case studies

This section presents the case study and simulation results of the proposed method. The capacity of EDWFs in a small community as VES and VPP are evaluated for four representative geographical areas.

5.1. Test bed

The test system consists of two parts: a water network and a power network of a small community at the distribution level. We have executed the proposed method on a WEN, including the IEEE 13-bus system and 8-Node EPANET WDS. Fig. 3 shows the topology of the WEN system for a small community. This testbed is suitable for a micro WEN in a small community. The network topology of a small community is no longer related to the geographical area. However, the EDWFs and loads are related to the geographical area due to the different availability of water resources [68]. We have considered different water resources and EDWFs in diverse areas with similar network structures to reach general conclusions. More specific information about testbeds for each geographical area is explained in the following sections.

Three types of electrical loads are connected to several buses. The first group is EDWFs loads include the water pump, the water treatment plant, the wastewater treatment plant, and the desalination plant, which are connected to bus 684, 652, 646, and 611, respectively. The components of these loads are different from area to area. Table 1 shows the information about the water supply and the EDWFs loads in different areas. The second one is the cooling load which is connected to bus 634. The cooling load, which is one of the largest power loads in the PDN, is modeled to increase the accuracy of the total load curve. The cooling load is given by [69]:

$$P_{i,t}^{\mathrm{Cool}} = \frac{G_{\mathrm{tot}}(T_{\mathrm{s}} - T_{\mathrm{o}}) + A_{\mathrm{j}} q_{\mathrm{floor}}}{\mathrm{COP_i}}. \tag{16}$$

We have considered the temperature of Orlando on July 28, 2019, which is shown in Fig. 4 [70], to calculate the cooling load. The third group is other electrical loads with a 24-hour load curve. Fig. 5 shows the 24-hour nodal prices and the load curve of these electrical loads [71]. The WDS of the test system consists of eight nodes and nine pipes, one pump station, and one tank. The water resource can consist of a water treatment plant, a wastewater treatment plant, a desalination plant, and groundwater based on their location and geographical specifications. The value of R^{w} is calculated based on the Darcy–Weisbach formula:

$$R^{\mathrm{w}} = f_{\mathrm{s}} \frac{L}{D} \frac{1}{2gA^2} = \frac{8 f_{\mathrm{s}} L}{\pi^2 g D^5}. \tag{17}$$

More details of the specification of the water network such as nodes elevation and length of pipes can be found at [37]. The optimal solutions are obtained by solving the objective functions using MOSEK solver in Yalmip (all simulations are executed in MATLAB R2019b environment with intel (R) Core (TM) i7-9700 CPU 3 GHz and 16 GB RAM). Yalmip is a toolbox for modeling and optimization in MATLAB. Yalmip can use several eternal solvers like MOSEK to solve the optimization problem [72]. MOSEK is a software package in the financial industry to solve optimization problems for linear, mixed-integer linear, quadratic, mixed-integer quadratic, quadratically constraint, conic, and convex

Table 2
Cost and BESS size and location for different case studies.

WDS type and scenario		Cost ($)				BESS	
		Total	Investment	Operation of BESS	Purchasing	Size (kWh)	Location
Urban	Sc I	1453.7	249.3	176.8	878.3	4016.5	Bus #684
	Sc II	1193.5	113	68.8	862.5	1728	Bus #611
Rural	Sc I	1431.1	246.7	175.4	859.6	3974.3	Bus #684
	Sc II	1196.9	131.2	82.8	833.5	2004.6	Bus #692
Desert	Sc I	1342.8	193.3	118.3	881.9	3060.8	Bus #611
	Sc II	714	–	–	714	–	–
Island	Sc I	1279.1	170.8	114.2	844.8	2709.9	Bus #684
	Sc II	950.1	15.3	9	776.5	222.6	Bus #652

nonlinear problems. Mosek package includes interfaces for MATLAB, Python, Java, R, .NET, and C/C++ [73].

5.2. Case I: Virtual energy storage

The power system is integrated with high penetration of PV resources (totally 2.5 MW) connected to three buses (633, 680, and 684) respectively. PV penetration is considered around 70% for four geographical areas. The unit costs of BESS are considered 209 $/kWh for energy capacity and 70 $/kW for power conversion system. Besides, a fixed cost of $ 545,000, including the installation, land acquisition, and permitting costs, is considered to limit the number of BESS units in the PDN [74]. Based on the literature review, the BESS operational cost is considered 0.005 ($ / kWh) and used for the simulation [53,75]. Two different scenarios are defined to execute on the small communities for four geographical areas to find the BESS size and location and evaluate the capacity of these EDWFs as a VES. First, all EDWFs operate without considering the WDS as a virtual system. Indeed, the WDS operates only based on their water demand. In the second scenario, the WEN operator can control the WDS operation as a VES. We discuss the results in the following paragraphs.

5.2.1. Urban area

The test power network of WEN in the urban areas consists of EDWFs including a pump and a water treatment plant, and other electrical loads. The total power consumption is 54.98 MWh of which 21.69% comes from the EDWFs. The BESS optimal size and location are calculated for two different scenarios regarding this area to minimize the total operational cost of the WEN system. The operational cost of this WEN is $1453.7 and $1193.5 for the first scenario and second scenario, respectively. It represents 17.90% of the revenue generated from controlling the EDEF as a VES. Indeed, without considering WEN as a VES, a BESS of 4016.5 kWh is needed, whereas, considering WEN as a VES, the needed BESS reduces to 1728 kWh. The WDS provides this capacity of VES by controlling the EDWFs such as OPS and changing the water production pattern. Figs. 6(a) and 6(b) show the WDS water production pattern and OPS for two scenarios in the urban area. For example, the pump status is OFF at hour 2, and the water treatment plant no longer works between 14 to 21 in the second scenario.

5.2.2. Rural area

The EDWFs, including a pump, a water treatment plant, a wastewater treatment plant, are considered for the test WDS in rural areas. The total power consumption of the PDN is 54.13 MWh of which 20.59% is related to the EDWFs. The total cost for providing power in the first scenario is $1431.1, which will be decreased to $1196.9 in the second scenario because of the BESS size reduction. Indeed, without considering WEN as a VES, a BESS of 3974.3 kWh is needed, whereas, considering WEN as a VES, the needed BESS reduces to 2004.6 kWh. Figs. 6(c) and 6(d) show that the WDS water production pattern and OPS depend on the scenario. For example, the pump status is OFF at hour 2 in the second scenario.

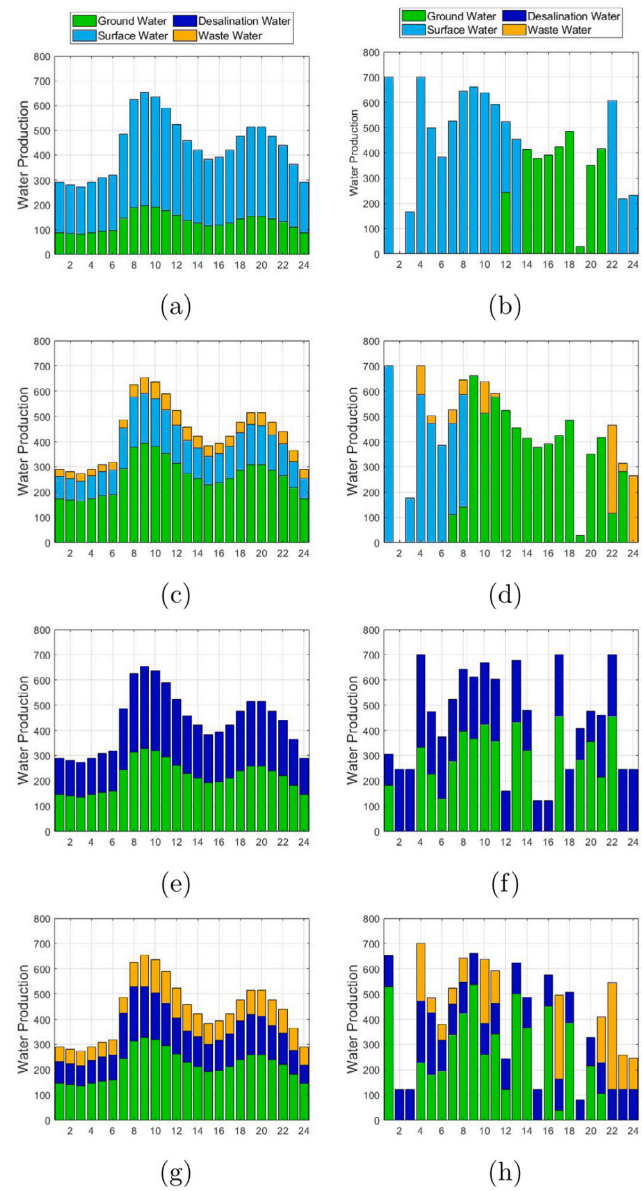

Fig. 6. Water production in different types of WDS and Scenarios: (a) Urban area (Sc I); (b) Urban area (Sc II); (c) Rural area (Sc I); (d) Rural area (Sc II); (e) Desert area near the sea (Sc I); (f) Desert area near the sea (Sc II) ; (g) Island area(Sc I); (h) Island area (Sc II).

5.2.3. Desert area near the sea

The test power network of WEN for the desert areas near the sea consists of EDWFs including a pump and a desalination plant, and

Table 3
Total operational cost of WEN for a small community by considering the WDS as a VPP in different areas.

Scenarios and areas		Cost and revenue ($)			Cost reduction compare to Sc I (%)	
		WEN	WDS	VPP revenue	WEN	WDS
Urban	Sc I	1283.5	273.5	–	–	–
	Sc II	1221.9	244.49	32.58	4.8	22.52
Rural	Sc I	1265.6	255.42	–	–	–
	Sc II	1211.4	232.2	30.96	4.28	21.21
Desert	Sc I	1276.3	476.6	–	–	–
	Sc II	1102	350.86	48.49	13.66	36.56
Island	Sc I	1324.2	342.2	–	–	–
	Sc II	1215	270.46	37.38	8.25	31.89

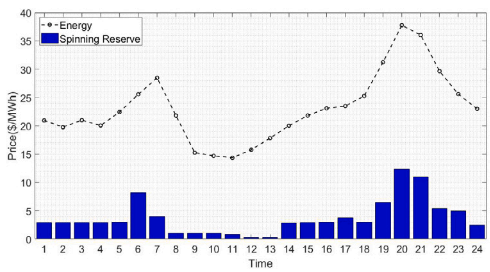

Fig. 7. Hourly energy and spinning reserve price.

other electrical loads. The total power consumption of the PDN is 55.56 MWh of which 38% comes from the EDWFs. The operational cost of this WEN is $1342.8 and $714 for the first scenario and second scenario, respectively. It represents 46.83% of the revenue generated from controlling the EDWFs as a VES. Indeed, the needed BESS can be zero by considering WEN as a VES. However, a BESS of 3060.8 kWh is needed without considering WEN as a VES. Figs. 6(g) and 6(h) show the WDS water production pattern for two scenarios in this area.

5.2.4. Island area

The EDWFs in the island area include a pump, a treatment plant, a wastewater treatment plant, and a desalination plant. The total power consumption of the PDN is 54.16 MWh of which 27.44% is related to the EDWFs. The total cost for providing power in the first scenario is $1279.1, which will be decreased to $950.1 in the second scenario because of the BESS size reduction. Indeed, without considering WEN as a VES, a BESS of 2709.9 kWh is needed, whereas, considering WEN as a VES, the needed BESS reduces to 222.6 kWh. Figs. 6(e) and 6(f) show the WDS water production pattern for two scenarios in this area.

The total operational costs of all scenarios are tabulated and compared in Table 2. The installation cost for all scenarios, except scenario II of the desert area near the sea, is $ 149.31.

5.3. Case II: Virtual power plant

In this section, the EDWFs are controlled as a VPP to participate in SR. The WEN operators of the small communities can operate the EDWFs to provide SR energy for the power grid. The 24-hour day-ahead energy and SR prices for July 1, 2020, of CAISO [76], as shown in Fig. 7 are used in the simulations. Two scenarios are executed to evaluate the capacities of the EDWFs as a VPP for each of the four geographical areas. First, the EDWFs are considered as fixed loads. In the second scenario, the capability of the EDWFs is investigated as a VPP. Indeed, the WEN operator can control the WDS operation to participate in SR. These scenarios are executed in the case studies for four types of geographical areas. Table 3 shows the results of these scenarios.

The water production and capacity of the small community WEN system as a VPP in different areas are compared for scenario I and scenario II in Fig. 8. These VPP capabilities can help the power grid

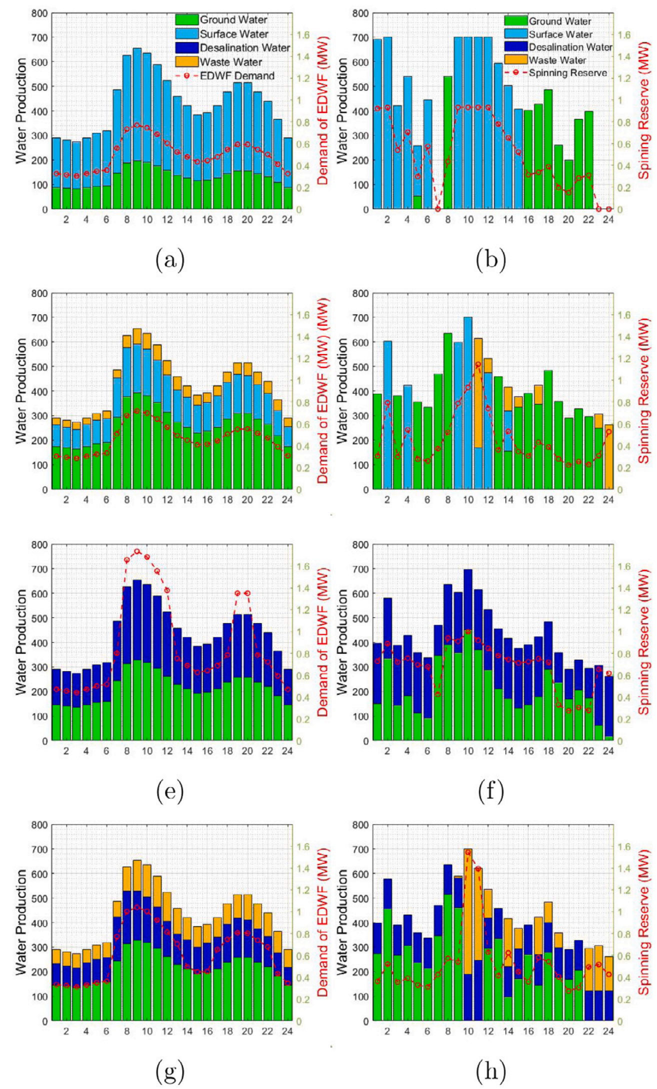

Fig. 8. Water production, WDS demand and SR capacity for Case II: (a) Urban area (Sc I); (b) Urban area (Sc II); (c) Rural area (Sc I); (d) Rural area (Sc II); (e) Desert area (Sc I); (f) Desert area (Sc II); (g) Island area (Sc I) (h) Island area (Sc II).

in balancing demand and supply by providing SR to the power grid frequency during emergency operating conditions or when the actual renewable power is drastically different from the forecasted one. The simulations show the operation cost of WDS can be reduced by 22.52%, 21.21%, 36.57%, and 31.89% for the selected test system in the urban area, the rural area, the desert area near the sea, and the island area, respectively. However, these reductions would be 4.8%, 4.28%,

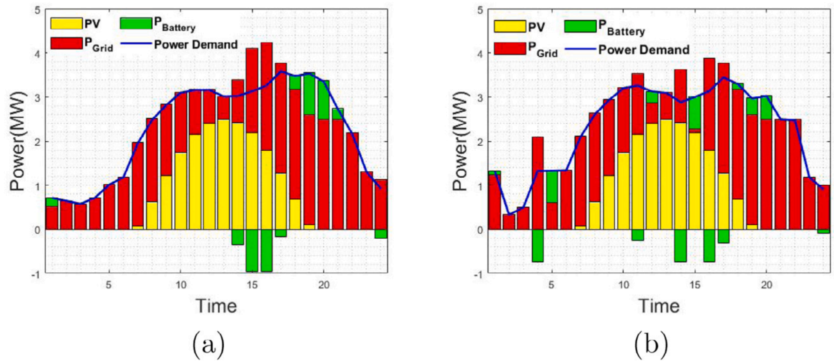

Fig. 9. Compares the operation of the BESS before and after applying our proposed approach in the urban area: (a) normal operation; (b) proposed method operation.

13.06%, and 8.25% for the operational cost of the WEN for these areas, respectively.

5.4. Prioritization of the WDSs in small community as VPP and VES for different areas

The capacities of EDWFs as VES and VPP are different from each other based on the above results. Table 4 shows the summary of the capability of the EDWFs in a small community for four types of geographical areas as VPP and VES. It can be observed from Table 4 that the EDWFs in the desert area near the sea have the most capacity to work as VES and VPP. The WDS in the island area has more capacity for working as VES than the WDS of the urban area. The WDS in the rural area has the least VES capacity. On the other hand, the WDS in the island area is the second priority to work as a VPP for the power grid. The WDS in the urban area and the rural area are the next priorities, respectively. To sum up, the simulations show that when the WEN operator of a small community controls the operation of the EDWFs as a VES, the small community, independent of its geographical area, incurs less cost. Therefore, it is more beneficial for small communities to consider EDWFs as a VES in a WEN.

5.5. Practical suggestions for WEN operator to improve the WEN operation

In this section, we provide some suggestions based on the results of our proposed method for WEN operators. The operation of a WEN can be improved by following such recommendations. We have recommended that the small communities can operate the EDWFs as a VES. The operators of the test system in this paper can decrease the size of the required BESS and reduce its related costs. For example, the BESS size can be decreased by 56.98% in a test system like our case study for the urban area by applying the proposed method. The charging and discharging of the BESS can be scheduled to reach the optimal operation of the PDN of the small community. Fig. 9 compares the operation of the BESS before and after applying our proposed approach. The small community decision-makers can postpone the required installation of BESS by applying our proposed method in the desert areas near the sea for a system like our case study. Although the BESS price is decreasing continuously, this instrument is still expensive. Therefore, the small community decision-makers can postpone purchasing this expensive instrument by considering the EDWFs as VES, and use this money for other emergency purposes.

Besides, It is possible to schedule water production in different water resources. For example, as shown in Fig. 6(b), the operator of the selected test system in the urban area no longer needs to use the produced water from the water treatment plant between 14 to 21. As a result, the owner of the water treatment plant can adjust the amount of personnel during these hours and assign them to work during the high-water-production hours, namely 1 to 11 and 22 to 24.

Table 4
Prioritization of the EDWFs as VPP and VES.

Area	Cost reduction of VES(%)	Cost reduction of VPP(%)	Best choice
Urban	17.90	4.8	VES
Rural	16.42	4.28	VES
Desert	46.83	13.66	VES
Island	25.72	8.25	VES

6. Conclusion and future work

This paper evaluates the capacity of EDWFs in small communities, such as small islands, campuses of universities/industrial parks/lab facilities, and remote villages/cities, as VES and VPP. Four types of WDSs are defined based on their location and geographical specifications to represent various areas in the world. The WEN operator can control EDWFs as VES or VPP to decrease the operational cost of WEN in the small communities. These costs can be reduced by 16.42% to 46.83% in systems like our case studies when the EDWFs serve as VES. Indeed, the needed BESS of WEN can decrease by 49.56% to 100% to achieve these cost reductions. For example, the results show the BESS requirement for a WEN system like our case study in the desert area near the sea will be eliminated by properly controlling the operation of EDWFs as a VES. Besides, EDWFs can provide SR as a VPP for the power grid, and decrease the operation cost of a WEN system like our case study in the small communities by 4.28% to 13.66%. This paper shows that the revenue from controlling the EDWFs as a VES for a small community, independent of its geographical area, is more than when the EDWFs serve as a VPP. Therefore, it is more beneficial to consider EDWFs as a VES in a WEN than considering them as a VPP for a power grid. The WEN operator can use this method to reach the optimal operation of a WEN integrated with high penetration of photovoltaic resources.

In future work, we will consider the demand uncertainty effect on the capacity of EDWFs as VPP and VES for a specific WEN. Besides, the signal price of electricity can be studied as a factor that may affect these virtual capacities.

CRediT authorship contribution statement

Mostafa Goodarzi: Methodology, Software, Data curation, Writing – original draft. **Qifeng Li:** Conceptualization, Validation, Writing – review & editing, Supervision.

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