Water-Energy Co-Optimization for Community-Scale Microgrids

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***Abstract*—A microgrid containing multiple energy sources typically serves localized loads in a small territory such as a small community and is intended to further improve the power security and sustainability for its service area. Since water supply is also very critical, this paper proposes a day-ahead water-energy co-optimization (WECoOp) model that simultaneously schedules both electric power and water for a community-scale microgrid. Therefore, the proposed WECoOp model will not only schedule distributed energy resources and exchange power with the main grid, but also manage local wastewater treatment, water storage reservoirs, and interaction with the main municipal water supply system. The necessary power and water related constraints are enforced in the proposed WECoOp model to ensure scheduling solutions are feasible and practical. To illustrate the effectiveness of the proposed WECoOp model, a benchmark case is established by implementing a normal microgrid energy management scheme while assuming the water is only supplied from the main water system. The case studies demonstrate the proposed water-energy co-optimization model can achieve significant operating cost savings.**

***Keywords*—Community Microgrid, Microgrid energy management, Microgrid water management, Water-energy co-optimization, Water treatment.**

Nomenclature

t	Time period index.
T	Time period set.
Δt	Duration of each time interval.
g	Power generator index.
G	Power generator set.
b	Energy storage unit index.
ES	Energy storage unit set.
s	Solar panel index.
SP	Solar panel set.
w	Wind turbine index.
WT	Wind turbine set.
k	Water storage unit index.
ST	Water storage unit set.
$P_{g,t}^{G}$	Power output of generator g at time interval t.
$P_{min,g}^{G}$	Minimum power output of generator g.
$P_{max,g}^{G}$	Maximum power output of generator g.
C_{g}^{G}	Generation cost of generator g.
NL_{g}^{G}	No load cost of generator g.
$u_{g,t}^{G}$	Status of generator g at time interval t.
SU_{g}^{G}	Startup cost of generator g.
$v_{g,t}^{G}$	Startup indicator of generator g at time interval t.
P_{t}^{grid+}	Power purchased from main grid at time interval t.
p_{t}^{+}	Main grid power purchase status at time interval t.
C_{t}^{grid+}	Main grid power purchase price at time interval t.
P_{t}^{grid-}	Power sold to main grid at time interval t.
p_{t}^{-}	Main grid power selling status at time interval t.
P_{limit}^{grid}	Main grid-microgrid exchange power limit.
C_{t}^{grid-}	Main grid power selling price at time interval t.
$PE_{b,t}^{d}$	Power discharged from storage unit b at time interval t.
$e_{b,t}^{d}$	Storage unit b discharging status at time interval t.
$PE_{b,t}^{c}$	Power charged to storage unit b at time interval t.
$e_{b,t}^{c}$	Storage unit b charging status at time interval t.
$PE_{limit,b}$	Charging/discharging limit of energy storage unit b.
$E_{b,t}$	Storage unit b charge level at time interval t.
$E_{min,b}$	Storage unit b minimum charge level.
$E_{max,b}$	Storage unit b maximum charge level.
$P_{s,t}^{SP}$	Power from solar panel s at time interval t.
$P_{w,t}^{WT}$	Power from wind turbine w at time interval t.
L_{t}^{R}	Power demand from residential loads at time interval t.
L_{t}^{C}	Power demand from commercial loads at time interval t.
W^{WW}	Volume flow rate of wastewater treated per unit of energy by the treatment unit.
L_{t}^{WW}	Power consumed by the wastewater treatment unit at time interval t.
NL^{WW}	Hourly operation cost of the wastewater treatment unit.
u_{t}^{WW}	Status of the wastewater treatment unit at time interval t.
W_{min}^{WW}	Minimum water supplied by the wastewater treatment unit.
W_{max}^{WW}	Maximum water supplied by the wastewater treatment unit.
WL_{t}^{WW}	Wastewater reservoir level of the treatment unit at time interval t.
WL_{max}^{WW}	Wastewater reservoir maximum level of the treatment unit at time interval t.
WR_{t}	Volume flow rate of wastewater collected into reservoir of the treatment unit at time interval t.
W_{t}^{main+}	Volume flow rate of water purchased from municipal system at time interval t.
C_{t}^{main+}	Price of water purchased from municipal system at time interval t.
a_{t}^{+}	Municipal system water purchase status at time interval t.
W_{t}^{main-}	Volume flow rate of water sold to municipal system at time interval t.
C_{t}^{main-}	Price of water sold to municipal system at time interval t.
a_{t}^{-}	Municipal system water selling status at time interval t.
$WS_{k,t}^{c}$	Water inflow of water storage unit k at time interval t.
$WS_{k,t}^{d}$	Water outflow of water storage unit k at time interval t.
$r_{k,t}^{c}$	Inflow status of water storage unit k at time interval t.
$r_{k,t}^{d}$	Outflow status of water storage unit k at time interval t.
$WS_{limit,k}$	Water storage k maximum flow rate.

$WL_{k,t}^{ST}$ Water storage k reservoir level at time interval t.
$WL_{max,k}^{ST}$ Water storage k maximum reservoir level at time interval t.
D_t^R Water demand from residential loads at time interval t.
D_t^C Water demand from commercial loads at time interval t.

I. Introduction

Microgrids are decentralized power management and distribution systems composed of multiple local energy resources such as controllable generation units, renewable energy sources (RES), and energy storage devices, all of which are managed simultaneously to meet demand. A microgrid energy management (MEM) system involving various energy sources such as solar panels and fuel cells, as well as a connection to the main grid is presented in [1]. It connects to the main grid through a point of common coupling, which makes the system a "*grid-tied*" microgrid. A microgrid with this configuration is capable of exchanging power with the main grid, obtaining electricity from the grid when there is insufficient local generation or when the electricity price is low, and exporting electricity when an excess of generation is present or when it is profitable.

Similar to the grid-connected MEM model, a system for microgrid water management (MWM) can be designed. There can be multiple clean water sources to meet the water demand in a microgrid. The optimal water dispatch can be implemented in a similar way to optimal power management. It can also deploy a unit commitment function to meet water demand to minimize total cost while enforcing constraints defined for water-related components, as presented in [2] that considers a multi-water resource economic dispatch model. However, [2] does not include energy economic dispatch. Moreover, coupling with the municipal water distribution system can be implemented as well, similar to the power coupling between a microgrid and the main grid.

Details about the relationship between electrical power and clean water distribution are discussed in [3], which presents a water-energy co-optimization model for large-scale bulk infrastructure systems whose generation technologies, such as thermal power generation, require substantial amounts of water to operate. However, in a microgrid, the distributed generating units such as microturbines and diesel generators are much smaller; they require negligible amounts of water to produce electricity or for cooling purposes [4].

A community-scale microgrid including a stormwater treatment unit is presented in [5]. However, the reclaimed water is only used for its hydrogen fuel cells which are implemented as energy storage devices, and no water is dispatched from the microgrid to meet water demand. For the microgrid used in this paper, the main relationship between water and energy would be the power consumption by the wastewater treatment process to produce clean water.

The use of renewable generation to directly meet the energy needs of a drinking water treatment plant is proposed in [6]. Similarly, [7] proposes the use of a renewable-based microgrid to power a water treatment plant only, while managing water dispatch for its consumers. Both [6] and [7] consider the power consumption of water treatment plants and propose MEM models to meet their power demands with renewables; however, they fail to consider the effective co-optimization of water and energy.

A formulation to optimize the energy consumption of water-energy systems at a community scale is proposed in [8], however, the model optimizes energy consumption of the water system pumps only, and it does not include energy consumption of water treatment processes in its model formulation, nor does it consider modeling of the co-optimization model of both resources under the same objective function and set of constraints.

A mathematical model for a micro water-energy nexus is presented in [9], whose optimization problem minimizes total operating cost of the power systems involved, with energy consumption by the water system pumps already included in its power balance constraint. Although [9] considers multiple water-inputs as well as water storage tanks, it models the power consumption of these inputs as only pumps, without modeling the energy intensity parameters of the treatment units.

To improve the microgrid efficiency and provide cost reductions for water and energy distribution, this paper proposes a day-ahead water-energy co-optimization (WECoOp) model for community-scale microgrids that simultaneously schedules power and water supply for a number of residential and commercial units. The proposed WECoOp model will involve unit commitment for both types of resources; and it incorporates the coupling between the microgrid and the main power grid, as well as the coupling between the microgrid and the municipal water system.

The rest of this paper is organized as follows. The proposed community microgrid WECoOp model is presented in Section II. Section III analyzes and compares the simulation results obtained with a normal MEM model and the proposed WECoOp model, respectively. Finally, Section IV concludes the paper.

II. Model Description

Due to the innate relation between water and energy, and the crucial demand for both types of resources, a microgrid capable of managing water and electrical energy distribution can be of interest to achieve greater efficiency and sustainability. Fig. 1 illustrates the framework of the proposed water-energy management system that can achieve this purpose. In Fig. 1, the red lines represent the electric power flow while the blue lines represent the water flow.

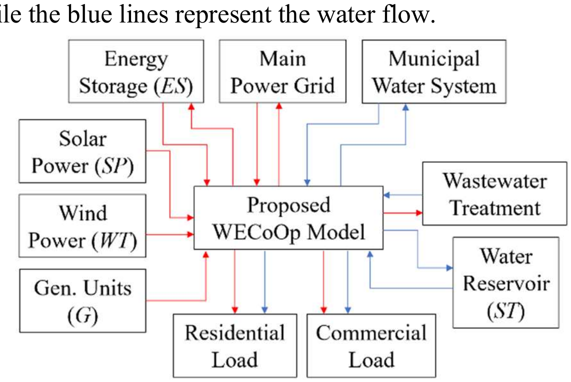

Fig. 1. Illustration of the proposed water-energy management system.

The proposed microgrid WECoOp model consists of different electrical energy and water sources and demands, including the coupling with the main power grid and municipal water system for bidirectional power and water exchanges, respectively. The electrical power sources are a number of controllable fuel-powered generation unis, solar panel arrays, and wind turbines. The water source is the wastewater treatment unit, which collects untreated wastewater and rainwater into a reservoir for subsequent treatment. The microgrid system also features energy storage devices, and clean water storage tanks. The loads are divided into two categories: residential and commercial, consuming both water and power.

The objective of this co-optimization model is to minimize the overall operation costs of generating power and treating water to meet the demands. The objective function of the proposed WECoOp model is defined in (1).

$$min\ f_{cost} = f_E + f_W \tag{1}$$

where f_E, and f_W denote the overall costs for meeting electrical load and water load respectively. They are expressed as follows,

$$f_E = \sum_{t\in T} \Delta t \cdot \left(\sum_{g\in G}\left(NL_g^G u_{g,t}^G + SU_g^G v_{g,t}^G + C_g^G P_{g,t}^G\right) + C_t^{grid+} P_t^{grid+} - C_t^{grid-} P_t^{grid-}\right) \tag{2}$$

$$f_W = \sum_{t\in T} \Delta t \cdot \left(NL^{WW} u_t^{WW} + C_t^{main+} W_t^{main+} - C_t^{main-} W_t^{main-}\right) \tag{3}$$

The constraints of the proposed WECoOp model can be divided into different categories encompassing all different features related to regulation and control operation of generators, power exchange with main grid, energy storage, water treatment, water storage, and water exchange with the main municipal water network. These constraints are presented in detail in the following subsections.

A. Microgrid Energy Management

The first group of constraints, (4)-(15), involve all the MEM variables and parameters for power dispatch. Constraint (4) enforces the output limits of each generator at every time interval, and (5) defines the relationship between the generator on/off status variable and the generator start-up variable. Constraints (6)-(7) set the power exchange limits between microgrid and main grid, while (8) ensures power is only either being exported to the main grid or imported into the microgrid at each time interval. Energy storage devices also introduce constrains regarding their discharge rate limit (9), charge rate limit (10), charge level (11), and minimum and maximum charge level (12). Constraint (13) ensures each energy storage device is only either charging, discharging or idle. Equation (14) represents the power balance constraint, which ensures the total power demand equates the total power supplied from the controllable-generation units, storage devices, and the main grid. Equation (15) represents the net load that is defined as the difference between total power demand and the power from RESs. For an energy-only scheduling model, the load L_t^{WW} from water treatment equipment would be zero.

$$P_{min,t}^G u_{g,t}^G \le P_{g,t}^G \le P_{max,t}^G u_{g,t}^G \ , \ (\forall g \in G, t \in T) \tag{4}$$

$$v_{g,t}^G \ge u_{g,t}^G - u_{g,t-1}^G \ , \ (\forall g \in G, t \in T) \tag{5}$$

$$0 \le P_t^{grid+} \le P_{limit}^{grid} p_t^+ \ , \ (\forall t \in T) \tag{6}$$

$$0 \le P_t^{grid-} \le P_{limit}^{grid} p_t^- \ , \ (\forall t \in T) \tag{7}$$

$$p_t^+ + p_t^- \le 1 \ , \ (\forall t \in T) \tag{8}$$

$$0 \le PE_{b,t}^d \le PE_{limit,b} e_{b,t}^d \ , \ (\forall b \in ES, t \in T) \tag{9}$$

$$0 \le PE_{b,t}^c \le PE_{limit,b} e_{b,t}^c \ , \ (\forall b \in ES, t \in T) \tag{10}$$

$$E_{b,t} = E_{b,t-1} + \Delta t \cdot \left(PE_{b,t}^c - PE_{b,t}^d\right) \ , \ (\forall b \in ES, t \in T) \tag{11}$$

$$E_{min,b} \le E_{b,t} \le E_{max,b} \ , \ (\forall b \in ES, t \in T) \tag{12}$$

$$e_{b,t}^c + e_{b,t}^d \le 1 \ , \ (\forall b \in ES, t \in T) \tag{13}$$

$$\sum_{g\in G} P_{g,t}^G + P_t^{grid+} - P_t^{grid-} + \sum_{b\in ES}\left(PE_{b,t}^d - PE_{b,t}^c\right) = L_t^{net} \ , \ (\forall t \in T) \tag{14}$$

$$L_t^{net} = L_t^R + L_t^C + L_t^{WW} - \sum_{s\in SP} P_{s,t}^{SP} - \sum_{w\in WT} P_{w,t}^{WT} \ , (\forall t \in T) \tag{15}$$

B. Microgrid Water Management

The second group of constraints, (16)-(27), involve all the MWM variables and parameters for water dispatch. The water flow limits for the wastewater treatment plant are defined in (16). Constraint (17) calculates the untreated wastewater reservoir level while (18) enforces the untreated wastewater reservoir capacity limits. Constraints (19)-(20) define the limits of water inflow and outflow rates of the clean water storage tanks, respectively. Constraint (21) calculates the amount of clean water in each tank at every time interval, and (22) enforces the capacity limits of each storage tank. Constraint (23) ensures that the tanks are only either storing or releasing water at every time interval. Constraints (24)-(26) define the water transfer limit between the microgrid and the municipal water system: (24)-(25) ensure the water rate limit is not violated and (26) guarantees that only water import or export is occurring at a time. Moreover, (27) represents the water balance constraint, which ensures all water treated and obtained from the main system and storage tanks equates the water demand by the residential and commercial customers.

$$W_{min}^{WW} u_t^{WW} \le W^{WW} L_t^{WW} \le W_{max}^{WW} u_t^{WW} \ , \ (\forall t \in T) \tag{16}$$

$$WL_t^{WW} = WL_{t-1}^{WW} + \Delta t \cdot (WR_t - W^{WW} L_t^{WW}) \ , \ (\forall t \in T) \tag{17}$$

$$0 \le WL_t^{WW} \le WL_{max}^{WW} \ , \ (\forall t \in T) \tag{18}$$

$$0 \le WS_{k,t}^c \le WS_{limit,k} r_{k,t}^c \ , \ (\forall k \in ST, t \in T) \tag{19}$$

$$0 \le WS_{k,t}^d \le WS_{limit,k} r_{k,t}^d \ , \ (\forall k \in ST, t \in T) \tag{20}$$

$$WL_{k,t}^{ST} = WL_{k,t-1}^{ST} + \Delta t \cdot \left(WS_{k,t}^c - WS_{k,t}^d\right) \ , \ (\forall k \in ST, t \in T) \tag{21}$$

$$0 \le WL_{k,t}^{ST} \le WL_{max,k}^{ST} \ , \ (\forall k \in ST, t \in T) \tag{22}$$

$$r_{k,t}^c + r_{k,t}^d \le 1 \tag{23}$$

$$0 \le W_t^{main+} \le W_{limit}^{main} a_t^+ \ , \ (\forall t \in T) \tag{24}$$

$$0 \le W_t^{main-} \le W_{limit}^{main} a_t^- \ , \ (\forall t \in T) \tag{25}$$

$$a_t^+ + a_t^- \le 1 \ , \ (\forall t \in T) \tag{26}$$

$$W^{WW} L_t^{WW} + W_t^{main+} - W_t^{main-} + \sum_{k\in ST}\left(WS_{k,t}^d - WS_{k,t}^c\right) = D_t^R + D_t^C \ , \ (\forall t \in T) \tag{27}$$

Therefore, the proposed WECoOp model consists of the objective (1)-(3) and constraints (4)-(27) while a microgrid energy scheduling model would only contain (2) and (4)-(15).

III. Case Studies

The water-energy co-optimization model presented in this paper is simulated with data for the Houston area. In the test microgrid system used in this paper, 60 residential units and 2 commercial units are considered. Their respective electrical demand profiles are obtained from the U.S. Department of Energy database [10], and their water demand profiles are determined based on the information presented in [3] and the average daily U.S. residential water consumption of 138 gal/day [11]. The controllable generation units include seven distributed generators with a combined maximum power output of 970 kW. The test microgrid also includes nine energy storage devices with a combined maximum charge level of 1335kWh and a combined maximum charge and discharge rate of 605 kW. For renewable generation, the test microgrid also includes multiple solar panels with a combined power capacity of 300 kW, and two wind turbines rated at 100 kW and 150 kW. Solar irradiance data were obtained from the NREL database [12] and wind speed data were obtained from Meteoblue [13]. The main grid-microgrid tie line has a maximum power transfer rating of 300 kW, and electricity prices throughout the day were based on the data from ERCOT [14]. The wastewater treatment unit features an untreated water reservoir with a capacity of 25,000 gal, and an energy intensity of 370 gal/kWh [4]. Reclaimed wastewater at the current time interval is defined as 50% of the water used by the water load from the previous interval. Moreover, there are four water storage tanks with a combined maximum capacity of 77,000 gal, and a combined maximum water flow rate of 2,450 gal/h. The maximum flow rate between the main water system and the microgrid is 3,000 gal/h. The cost of water is set to the average water cost in Texas which is about \$0.01/gal for every hour of the day, according to [15].

In order to demonstrate the benefits of the proposed WECoOp model, a benchmark case is established by optimally scheduling energy only in a traditional manner. For this benchmark case, the water is supplied from the main municipal water system and there is no local water management within the microgrid. The results of such a benchmark case are compared to those of a water-energy simultaneously scheduled case with the proposed WECoOp model. Both cases are simulated in MATLAB using the CVX optimization toolbox with Gurobi as the optimization solver. Both cases are simulated for a time period T of 24 hours with 24 one-hour intervals.

A. Microgrid Energy Management Only

The simulation is performed on the benchmark case with only MEM being executed and with all the water demand met from the main municipal system. The breakdown of energy schedules by source, as well as the total net load, are displayed in Fig. 2. Fig. 3 presents the total energy storage level as well as the main grid cost of electricity. Fig. 4 shows the total water demand, which is completely met by the main water system in this case.

The power demand is met with various resources in the most optimal way that leads to the lowest operating cost. In Fig 3, it can be seen how energy storage aids in reducing the cost by storing energy when the electricity price is low and releasing it later during expensive hours. Moreover, in Fig. 2, it can also be noted how the distributed generators increase their total output during peak hours of high electricity price, indicating that the cost of importing power from the main grid is higher than the cost of local generation at those hours.

The resulting optimal operating cost of this MEM only case is \$2,909.73, which includes the cost of running local generators, the cost of exchanging power with the main grid, and the cost of the water obtained from the main water system to meet the water demand.

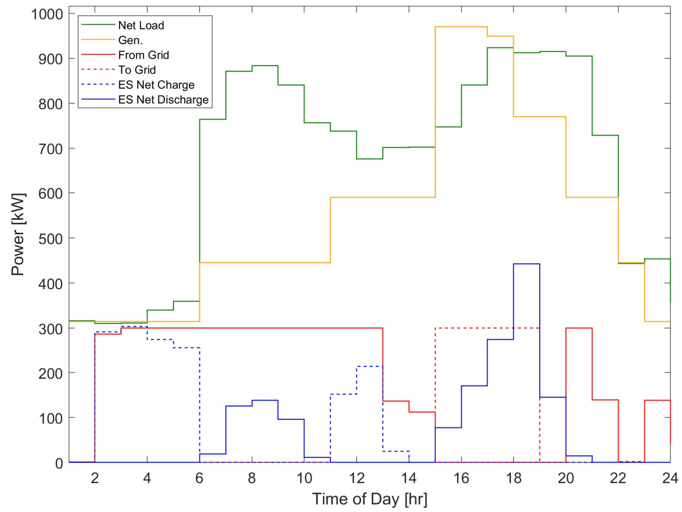

Fig. 2. Power schedule for MEM only benchmark case.

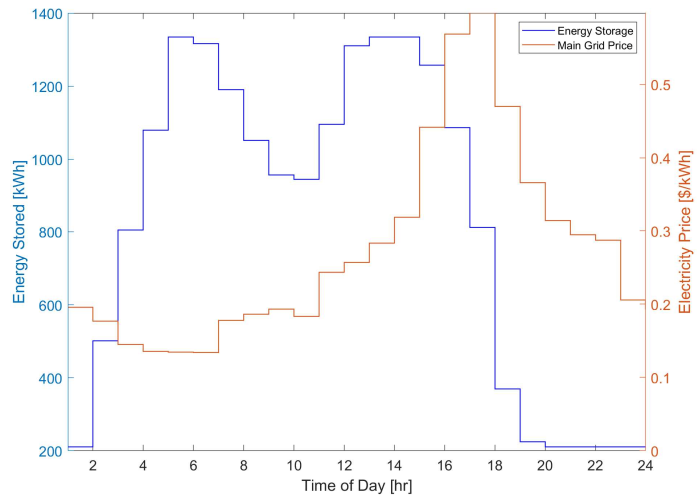

Fig. 3. Total energy storage level and grid price in MEM only benchmark case.

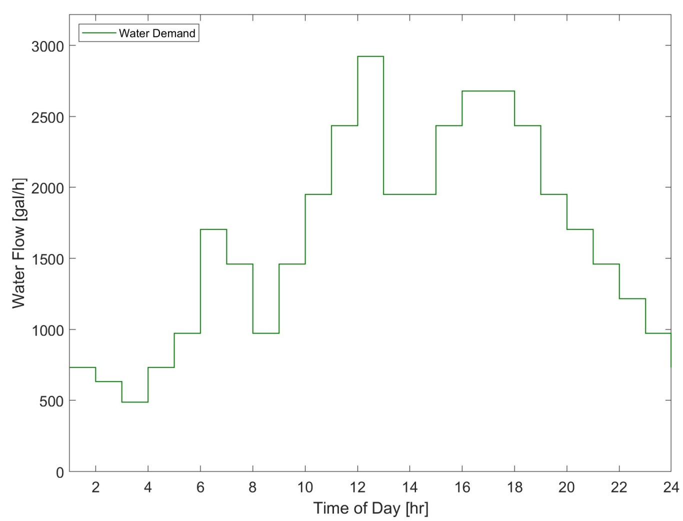

Fig. 4. Water demand for MEM only benchmark case.

B. Microgrid Water-Energy Management

The water-energy management case is simulated on the test microgrid system and the water-energy co-optimization problem is solved with the proposed WECoOp model. In addition to power management, this case also takes water management into account. Note that the power consumption associated with local wastewater treatment is added to the net electrical load. The day-ahead power supply schedule is displayed in Fig. 5; the total energy storage level as well as the main grid cost of electricity for this case are illustrated in Fig. 6; and the day-ahead water supply schedule is presented in Fig. 7.

The water demand profile used in this case is still the same as in the benchmark case; however, the net electrical load is slightly higher as a result of the fact that the local water treatment unit consumes additional power. This causes the power schedule obtained with the proposed WECoOp model to be slightly different from the benchmark case. The breakdown of water supply in Fig. 7 shows that various water sources are used to meet demand in a similar way to the power supply in Fig. 5 to meet power demand.

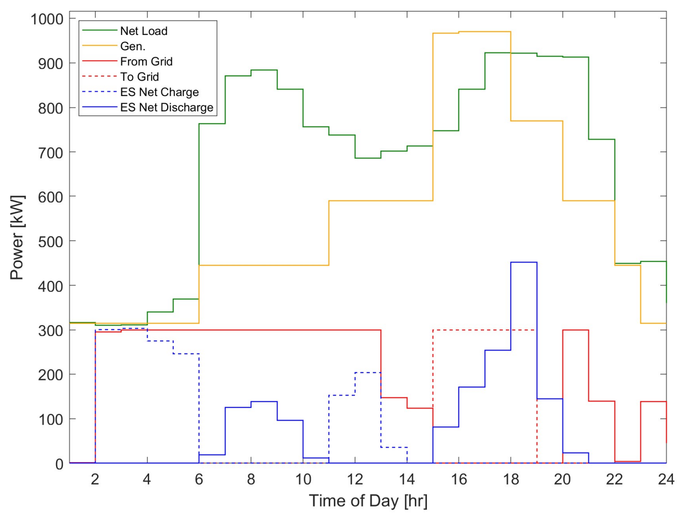

Fig. 5. Power schedule for water-energy co-optimization case.

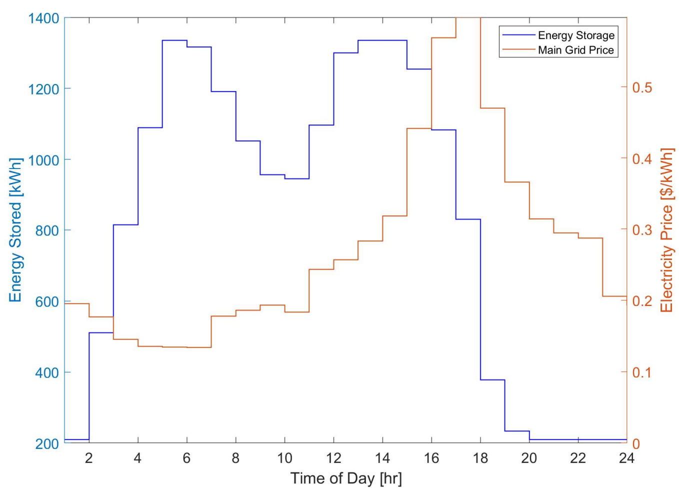

Fig. 6. Total energy storage level and grid price in water-energy co-optimization case.

Even though the water cost from the main system remains constant throughout the entire 24-hour period, the co-optimization model still prioritizes the use of the local wastewater treatment plan to treat water when the total cost of power for treatment is lower than what it would be by purchasing water from the main system instead. The water storage tanks are also used in a similar manner to the energy storage devices.

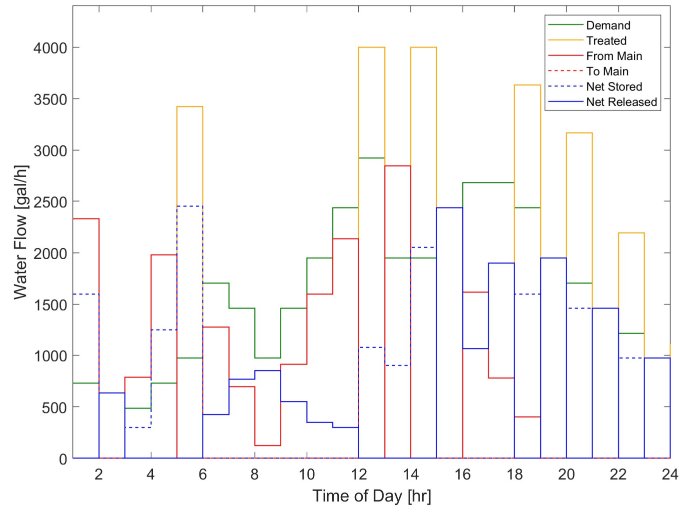

Fig. 7. Water schedule for water-energy co-optimization case.

The resulting optimal operating cost with the proposed WECoOp model is $2718.59, indicating a substantial reduction of $191.14 or 6.57% from the benchmark case with MEM only. Table I shows the detailed cost results of both cases. Although the total power cost is slightly lower for the MEM only case, its water cost is around two times higher than the proposed WECoOp model. This leads to a much higher overall cost when not co-optimizing water and energy.

Table I: Costs for the MEM only and water-energy cases.

	MEM only	Water-Energy	Difference
Energy	$2523.32	$2539.69	$16.37 (0.65%)
Water	$386.41	$178.90	$207.51 (53.70%)
Total	$2909.73	$2718.59	$191.14 (6.57%)

IV. Conclusions

A water-energy co-optimization model for a community-scale microgrid is proposed in this paper. It consists of MEM and MWM systems simultaneously managing electrical energy and water to meet demand while also meeting all system and operation constraints. The system features a connection to the main electrical grid, as well as a connection to the main municipal water system; this enables power and water exchange with the utility-scale infrastructures. Two cases are simulated. In the benchmark case, a traditional microgrid that optimizes energy only, without local water management, is simulated. The second case implements the proposed WECoOp model that co-optimizes both water and power resources to meet both types of demand simultaneously. The results on these two cases show that a local water-energy management system achieves a significant reduction of 6.57% in microgrid operating cost since the inclusion of MWM decreases the cost of meeting water demand by 53.7%. This demonstrates the effectiveness of the proposed WECoOp model that allows both types of resources to be scheduled optimally to meet water and electrical demands with a least cost for community-scale microgrids.

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