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Robust Energy-Water Management of a Self-healing Complex Based on System-of-Systems

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***Abstract*— The efficient and resilient energy-water management of a residential/commercial complex with four buildings is studied in this paper. It is assumed that each building is autonomous in terms of energy production. The water demand of these buildings is acquired through a desalination and filtration system, which is connected to a utility grid to draw the required energy. Normally, the buildings are separately connected to the distribution network. However, during outages, the buildings within the complex share their resources to confront the energy deficiency to serve the electric loads and water desalination energy demand. Each building is furnished with a diesel generator, which is in charge of being a backup resource. Moreover, the integration of renewable energy resources and electric storage created a sustainable and green energy complex. The intermittent generation of wind and solar systems is managed by robust counterparts in the proposed optimization problem. The proposed framework is tested in two cases and the results prove the effectiveness of the proposed energy-water management plan.**

Keywords*— *Energy and water management, desalination system, resiliency, system-of-systems framework, robust optimization approach.

Nomenclature

Symbols	***Definition***
t, T	Index of time (Hour)
b, B	Index of buildings
λ_t^g	Energy price of utility grid ($/kWh)
λ_b^{dg}	Energy price of diesel generator ($/kWh)
$\overline{P_b^{ch}}$, $\overline{P_b^{d}}$	Maximum allowable charging and discharging powers of battery (kW)
$\underline{E_b^{bat}}$, $\overline{E_b^{bat}}$	Minimum/maximum allowable state of energy of battery (kWh)
$\overline{P_b^{dg}}$	Maximum power capacity of diesel generator (kW)
$\overline{P^g}$	Maximum exchangeable power with utility grid (kW)
$\overline{P_{b,b'}^{flow}}$	Maximum power flow between buildings within the complex (kW)
$\underline{P_{t,b}^{ren}}$, $\overline{P_{t,b}^{ren}}$	Minimum/maximum forecasted power generation by renewable resources (kW)
$P_{t,b}^{load}$	Actual electric load demand (kW)
H_t^{demand}	Actual water demand (m^3)
$C_{t,0}^{\text{tank}}$	The capacity of water storage (m^3)
$P_{t,b}^g$	Exchanged power with utility grid (kW)
$P_{t,b}^{dg}$	Generated power by diesel generators (kW)
$P_{t,b}^{PV}$	Generated power by solar systems (kW)
$P_{t,b}^{wind}$	Generated power by wind resources (kW)
$P_{t,b}^{ch}$, $P_{t,b}^{d}$	Charged and discharged powers by battery (kW)
$E_{t,b}^{bat}$	The energy state of the battery (kWh)
$P_{b,b',t}^{flow}$	Power flow between buildings within the complex (kW)
$P_{t,b}^{DRP}$	Served demand after demand response (kW)
$P_{t,b}^{LSH}$	Shifted demand after demand response (kW)
$P_{t,0}^{Des}$	Consumed power by desalination unit (kW)
$H_{t,0}^{Des}$	Produced freshwater by desalination unit (m^3)
$H_{t,0}^{C}$, $H_{t,0}^{D}$	Charged/discharged water of water storage (m^3)
$y_{t,b}^1$, $y_{t,b}^2$	Auxiliary variables of robust counterparts
Z^1 , $\delta_{t,b}^1$, Z^2 , $\delta_{t,b}^2$	Dual variables used in robust optimization transferring into single-level problem
Γ	Robustness controlling parameter

I. INTRODUCTION

The development of renewable energies and deregulated power markets welcomed residential and commercial buildings to energy transactions, especially, in remote areas to enhance the reliability, sustainability, and resiliency of the power supply. Intrinsically, the installed generation and storage capacity is acted as backup capacity due to utility grid connection. In the faulty conditions, the complex is split into several separate buildings with different energy production and consumption characteristics which increases the vulnerability against load curtailment. On the other hand, for remote areas, the water demand can be served through the purification of local brackish waters. The desalination process does require a huge amount of energy, which is procured by the utility grid. The outlining of the system-of-systems (SOS) concept solves resiliency and durability issues in the residential complexes to continuously serve electric and water demands. In the SOS framework, the sub-systems make some or all of their resources available for the rest of the system to increase functionality and performance. The SOS framework designed in various arrangements [1] could be utilized for resilient and cost-efficient energy management of residential and commercial complexes. The energy management of smart buildings was extensively focused over the past years, in particular considering the operative uncertainty of renewable generation and load behavior. The self-scheduling problem of a smart home that participates in energy markets is inspected in [2] using stochastic-based interval optimization to investigate the effects of uncertainties of electricity price and renewable generation. In [3], a hybrid stochastic-robust optimization approach is proposed to cope with uncertainties of smart home energy management problem that results in risk-neutral and risk-averse scheduling. With detailed load models, the authors of [4] presented a stochastic model for energy management of smart homes considering the thermal and electrical load consumption uncertainties in the presence of intermittent renewable generation. In [5], a method for smart home energy management is directed by efficient use of demand response programs is proposed based on chance-constrained optimization problems. In addition to energy generation, water production is essential for remote areas, which do not have access to global water plumbing. In this regard, an evaluation model is developed in [6], using HOMER software that utilizes a hybrid solar-wind generation system for water desalination through reverse-osmosis (RO) process. In addition to the energy economy, enhancing the resiliency in power and energy systems is of great significance. The resiliency, despite reliability, ensures the functionality of the studied system during and after certain faults, from the viewpoint of consumers [7]. Integrating the concept of resiliency in smart buildings management brings the self-healing capability and decreases the occupant's dissatisfaction. The main options for grouped buildings are peer-to-peer and SOS plans that allow the common use of extra resources of each sub-system based on predefined rules and agreements. Concerning resilience-oriented energy management of smart buildings, the authors of [8] addressed the resiliency of two residential and commercial buildings through peer-to-peer energy trading and a shared electric vehicle station to minimize the energy cost and maximize the energy resiliency during power outages without further investments. A comprehensive study is done in [9] that discussed the methods, barriers and advances of peer-to-peer energy sharing for communities. It also reviews different pilot projects and power-sharing technologies around the world. The use of the SOS framework is prescribed in [10], for four microgrids that share their resources during emergencies and increase the whole system functionality and energy efficiency to achieve zero load curtailment. However, for single buildings, resiliency-based energy management can be assessed with the help of storage devices and demand-side management tasks. Concerning the regulatory issues, a power-sharing model is proposed by [11] for the energy communities of buildings in Simulink/MATLAB environment. The model investigates the self-consumption and aggregated operation in the presence of renewable energy, while it does not discusses about the uncertainty and energy resilience. The complex studied in this paper consists of four autonomous buildings that are electrically connected through tie-lines, and each of them is bi-directionally connected to the main grid to buy or sell the energy directly or by a middleman. The water system is also supplied by the grid under normal operation conditions. Each of the buildings are equipped with different energy sources that will be shared under faulty conditions, when the grid is not available to achieve a low-cost energy dispatch and to provide the required energy for the desalination unit to refine the saline water. A sketch of the complex is depicted in Fig. 1.

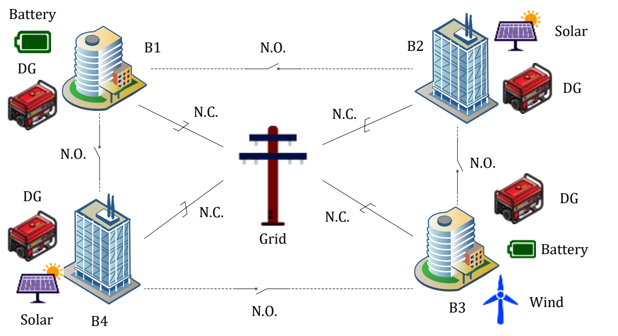

Fig. 1. Schematic of SOS-based self-healing complex: the normally open (N.O.) breakers make it available to share resources under faulty conditions.

The contributions of the presented paper can be listed as follows:

- Proposing the concept of SOS in energy-water management of a residential complex with a novel arrangement to enhance the resiliency.
- Incorporation of water desalination system for autonomous pure water production within the complex.
- Optimal scheduling of resources, including energy and water storage systems and demand-side management for cost minimization and resiliency increment.
- Dealing with uncertain power generation of solar and wind resources using linear robust counterparts.

The paper is organized as follows. The mathematical problem modeling is presented in Section II. The case study descriptions and numerical evaluations are reported in Section III and conclusions are provided in Section IV.

II. Problem Modeling

The energy management system of the studied complex is founded based on the SOS structure. In this architecture, each sub-system, i.e., building, acts autonomously under normal operation condition and send/receives energy scheduling signals to/from the utility [12]. The sub-systems are geographically distributed, where under the faulty condition, they are centrally controlled to optimally share their resources and achieve efficient energy dispatch. The water desalination unit consumes considerable electric energy to refine the saline water. Hence, it is connected to the grid under normal operation. However, in the lack of grid connection, the aid of buildings is providing its required energy to serve water demand. To assure the operation security, under the faulty conditions, the buildings take part in the time-of-use demand response program to increase the scheduling flexibility. In the following, the general formulation for risk-neutral and risk-averse energy-water management of the complex is presented based on the SOS scheme.

A. Risk-neutral energy-water management

The objective function of the complex energy management problem is minimizing the energy cost charged by utility grid and diesel generator (DG) fuel expense. Note that each building can sell extra power to the grid by corresponding hourly energy prices. The objective function is written in (1).

$$Min \qquad Cost=\sum_{t=1}^{T}\sum_{b=1}^{B}(P_{t,b}^{g}\times\lambda_t^{g})+(P_{t,b}^{dg}\times\lambda_b^{dg}) \tag{1}$$

Under both normal and faulty conditions, the limiting constraints are expressed as (2) for maximum exchangeable power, and for DGs indicated by (3).

$$-\overline{P^{g}}\le P_{t,b}^{g}\le\overline{P^{g}} \tag{2}$$

$$0\le P_{t,b}^{dg}\le\overline{P_b^{dg}} \tag{3}$$

Constraints (4)-(8) stand for the electric storage, in which the maximum charging and discharging powers are limited by (4) and (5). The storage cannot be charged and discharged at the same time, which is modeled by (6). The state of energy at each timeslot can be calculated based on (7) according to charging, discharging powers and efficiency. The state of energy should be within the standard defined in (8) and (9).

$$0\le P_{t,b}^{ch}\le\overline{P_b^{ch}}\times x_{t,b}^{ch} \tag{4}$$

$$0\le P_{t,b}^{d}\le\overline{P_b^{d}}\times x_{t,b}^{d} \tag{5}$$

$$x_{t,b}^{ch}+x_{t,b}^{d}\le 1 \tag{6}$$

$$\begin{aligned}E_{t,b}^{bat}&=E_0+P_{t,b}^{ch}\eta^{ch}-\frac{P_{t,b}^{d}}{\eta^{d}},(for\,t=1)\\E_{t,b}^{bat}&=E_{t-1,b}^{bat}+P_{t,b}^{ch}\eta^{ch}-\frac{P_{t,b}^{d}}{\eta^{d}},(for\,t>1)\end{aligned} \tag{7}$$

$$\underline{E_b^{bat}}\le E_{t,b}^{bat}\le\overline{E_b^{bat}} \tag{8}$$

$$E_0=E_{t,b}^{bat},(for\,t=T) \tag{9}$$

The water desalination system considered in this study utilizes reverse-osmosis technology and post-filtration processes for the purification of available brackish water. In this mechanism, only electric energy is needed. The desalination system modeling is described below based on [13]. The water system of the complex is equipped with a water tank which is charged and discharged based on the management plan. Under normal operation, the water system is electrically connected to the utility grid indexed by b=0. The water balance is accomplished by (10). The electric power consumption of the desalination system is related to water production volume through conversion constant η^{e} in (11). The hourly generation capacity of the desalination system is proportioned to the total daily production capacity by (12). Similar to electric storage, the water storage constraints are presented as (13)-(17). The last equality constraint (17) assures that the status of the storage at the end of the operation horizon is the same as the initial status. It should be noted that the water charging and discharging duration time is 1 hour.

$$H_{t,0}^{Des}+H_{t,0}^{D}-H_{t,0}^{C}=H_t^{demand} \tag{10}$$

$$P_{t,0}^{Des}=H_{t,0}^{Des}\times\eta^{e} \tag{11}$$

$$H_{t,0}^{Des}\le {}^{1}\!/_{24}H_{total}^{Des} \tag{12}$$

$$0\le H_{t,0}^{C}\le\overline{H_{t,0}^{C}}\times u_{t,0}^{C} \tag{13}$$

$$0\le H_{t,0}^{D}\le\overline{H_{t,0}^{D}}\times u_{t,0}^{D} \tag{14}$$

$$u_{t,0}^{C}+u_{t,0}^{D}\le 1 \tag{15}$$

$$\begin{aligned}C_{t,0}^{tank}&=C_{0,0}^{tank}+H_{t,0}^{C}-H_{t,0}^{D},(for\,t=1)\\C_{t,0}^{tank}&=C_{t-1,0}^{tank}+H_{t,0}^{C}-H_{t,0}^{D},(for\,t>1)\end{aligned} \tag{16}$$

$$\sum_t H_{t,0}^{C}=\sum_t H_{t,0}^{D} \tag{17}$$

Finally, the energy balance of the system under both normal and faulty modes is presented by (18) and (19), respectively.

$$P_{t,b}^{g}+P_{t,b}^{dg}+P_{t,b}^{PV}+P_{t,b}^{wind}-P_{t,b}^{ch}+P_{t,b}^{d}-P_{t,0}^{Des}-P_{t,b}^{load}=0 \tag{18}$$

$$P_{t,b}^{dg}+P_{t,b}^{PV}+P_{t,b}^{wind}-P_{t,b}^{ch}+P_{t,b}^{d}-P_{t,0}^{Des}-P_{t,b}^{DRP}+P_{t,b}^{LSH}=\sum_{b'}P_{b,b',t}^{flow} \tag{19}$$

Comparing the abovementioned constraints reveals the differences between separated and SOS-based operations. The absence of term $P_{t,b}^{g}$ in (19) confirms that the utility grid is disconnected in the faulty mode. The energy flow between connected buildings is shown by $P_{b,b',t}^{flow}$ creates the opportunity for each building to share exceed energy resources. It should be pointed out that buildings' demand is also managed to impose less burden during peak times by using a time-of-use demand response program (DRP). In this scheme, the load is shifted from critical points to off-peak and median times to reduce energy consumption and increase efficiency and resiliency. The electric load model considering the time-of-use program can be formulated as follows.

$$P_{t,b}^{load}=P_{t,b}^{DRP}+P_{t,b}^{LSH} \tag{20}$$

$$-0.2\times P_{t,b}^{load}\le P_{t,b}^{LSH}\le 0.2\times P_{t,b}^{load} \tag{21}$$

$$\sum_{t,b}(P_{t,b}^{DRP}+P_{t,b}^{LSH})=\sum_{t,b}P_{t,b}^{load} \tag{22}$$

$$\sum_t P_{t,b}^{LSH}=0 \tag{23}$$

From (20), a part of the electric load at each time is a base value that should be supplied. While a part is shifted to the other times and limited in (21). From (22), the sum of base load and shifted load over the day should be equal to the sum of actual daily load consumption. Moreover, the last constraint (23) assures that for each building, the total amount of shifted load during the daily operation is zero.

B. Risk-averse energy-water management

In order to investigate the effects of the uncertain generation of solar and wind resources on the energy-water management of the complex, a robust optimization approach is applied. The robust optimization is inherently structured as bi-level programming, which minimizes the energy cost subject to the maximization of uncertainty effects. The original problem can be transferred into a single-level optimization by exerting the strong duality theorem. In this regard, the robust counterparts crucially model the negative impacts of uncertain parameters on the optimization problem. For more information, the interested readers are referred to [14], [15].

The energy balance constraint for the normal operation condition can be written as follows considering the robust counterparts to involve the effects of uncertainties of solar and wind generation.

$$\begin{aligned}&P_{t,b}^{g}+P_{t,b}^{Dis}+(P_{t,b}^{PV}-Z^{1}\Gamma-\delta_{t,b}^{1})+(P_{t,b}^{wind}-Z^{2}\Gamma-\delta_{t,b}^{2})\\&-P_{t,b}^{ch}+P_{t,b}^{d}-P_{t,0}^{net}-P_{t,b}^{load}=0\end{aligned} \tag{20}$$

$$Z^1+\delta^1_{t,b} \le (\overline{P^{PV}_{t,b}} - \underline{P^{PV}_{t,b}}) \times y^1_{t,b} \quad (21)$$

$$y^1_{t,b} \ge 1 \quad (22)$$

$$Z^2+\delta^2_{t,b} \le (\overline{P^{wind}_{t,b}} - \underline{P^{wind}_{t,b}}) \times y^2_{t,b} \quad (23)$$

$$y^2_{t,b} \ge 1 \quad (24)$$

For the faulty condition, the energy balance constraint could be written similarly. Hence, the optimization problem (1)-(18) and (20)-(24) represent the robust energy-water management of the complex under normal operation.

III. Numerical Evolutions

The proposed robust energy-water management scheme is tested on a four-building complex, as shown in Fig. 1, which is connected to the utility grid to deal with the energy surplus. Moreover, the water demand of the complex is obviated using a desalination unit with a total daily production capacity of 200 m^3. The DGs of the buildings are preserved as backup energy resources, with a total capacity of 30, 10, 15, and 5 kW, respectively for B1, B2, B3, and B4 that are equal to the peak electric demands. Buildings B1, and B3 are equipped with battery storage with nominal characteristics as 30kWh/10kW and 15kWh/5kW, with unit charging/discharging efficiency. Each building can exchange below 1 MW with the grid under normal operation. Buildings B2, B3, and B4 are equipped with renewable energy where the forecasted generation pattern, the load profiles of the buildings and energy price of the grid are adopted from Ref. [10]. The peak accumulated demand of the water is assumed 7m^3, where the hourly profile of water demand is adopted from Ref. [13]. The technical values of the water refining unit, including the RO-based desalination system and water storage, are provided in Table I.

To obtain the risk-averse scheduling plan, it is assumed that the actual wind and solar generations, respectively, have ±20% and ±5% errors from the forecasted values. The robustness controlling parameter (Γ) is increased from zero (indicating the risk-neutral case without considering the effects of uncertainties) to one (i.e., the most conservative case with full inclusion of uncertainty effects) by 0.1 steps. The proposed adjustable robust optimization results in several scheduling plans, where the risk-neutral (Γ=0) and risk-averse (Γ=1) paradigms are reported here.

Under normal operation, the buildings trade the energy with the grid. The bought and sold powers are respectively indicated by positive and negative values in Fig. 2, for each building for both risk-neutral (deterministic) and risk-averse (robust) strategies.

From Fig. 2, the exchanged powers with the utility grid are linked to the generation of renewable resources for buildings B2, B3, and B4, while the operation of B1 is not constrained by the robust strategy. Moreover, due to restrictions on renewable generation under the robust case, buildings B2, B3, and B4 have bought more and sold less power from/to the grid. The robust optimization by modeling the worst situation caused by uncertainty schedules the energy system to reduce the financial risk within the predefined uncertainty intervals. As the uncertainty interval for wind generation is assumed more extensive than solar generation, the operation of building B3 is more intervened by the robust approach in comparison with B2 and B4. The DGs of buildings are requested to generate energy in emergency times. Hence, under normal operation, it is not expected to generate power due to grid connection.

TABLE I. Water system characteristic

η^e	H^{Des}_{total}	$\overline{H^C_{t,0}}$	$\overline{H^D_{t,0}}$	$\overline{C^{tank}_{t,0}}$
2.2 (kW/m^3)	200 (m^3/day)	0.5 (m^3/h)	0.5 (m^3/h)	2.5 (m^3)

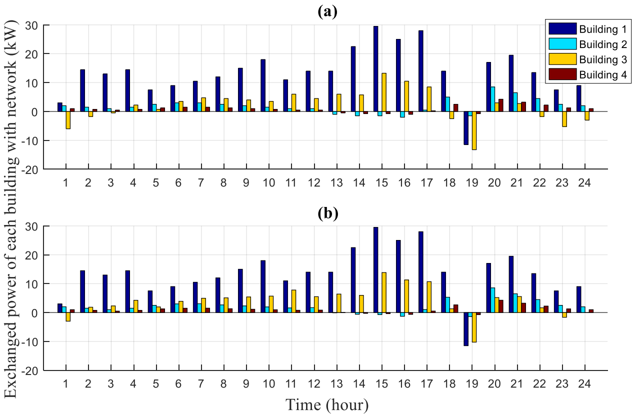

Fig. 2. Exchanged power of each building with network under normal operation for: (a) deterministic case with forecasted renewable generation, (b) robust case with considering full budget of uncertainty for renewables.

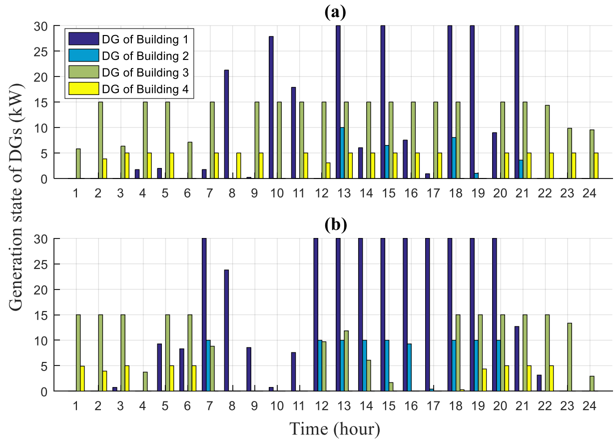

Fig. 3. Electric power generated by DGs under faulty conditions: (a) for the deterministic case with forecasted renewable generation, (b) for the robust case with considering full the budget of uncertainty for renewable generation.

In this regard, only at 7 p.m., the DGs of buildings are committed to generating electric power at the maximum level to sell it to the grid with high energy prices. This is done under both deterministic and robust cases in the normal operation. However, under the faulty conditions where the grid connection is lost, the DG commitment is ineluctable to supply the electric loads and water desalination unit's demand. Figure 3 shows the state of energy generated by DGs under faulty conditions.

It should be noted that under faulty conditions, the energy scheduling is conducted based on SOS and buildings pool their resources to increase efficiency. For this reason, the complex can be imagined as a single building with various energy resources, and the effects of renewable energy resources are alleviated.

It is foreseen that the energy dynamics of the battery storage would be different for normal and faulty conditions. The dynamics of the battery are shown in Fig. 4, in which positive values stand for charging powers and vice versa. It is seen that under the normal condition, a similar pattern is deduced for both deterministic and robust cases because the batteries are used for the energy arbitrage with maximum capacity due to energy price fluctuations. While under the faulty mode, the battery storages compensate the renewable resources' output and increase the flexibility.

In Fig. 5, the desalination unit's water production states are depicted. Accordingly, the amount of water production in deterministic and robust strategies is different. Under normal operation in the deterministic case, the desalination unit only procures the water demand, while under robust strategy does not exactly match the water demand. It is also true for the faulty condition for both deterministic and robust cases. The water storage beside the desalination system provides consistency. A breakdown of Figs. 5 and 6 can be interpreted as follows: under restricted conditions, a fair utilization of water storage is planned to enhance the flexibility, while under normal operation, the desalination system is connected to the grid.

Under the faulty conditions, the energy management system enables the DRP to decrease the cost and increase resilience. Not surprisingly, the load consumption scheduling is different for deterministic and robust cases, which is shown in Fig. 7. It should be noted that the maximum amount of load deviation is ±20% to keep the inhabitants' comfortable. The energy costs are compared in Table II for normal and faulty conditions for different risk levels.

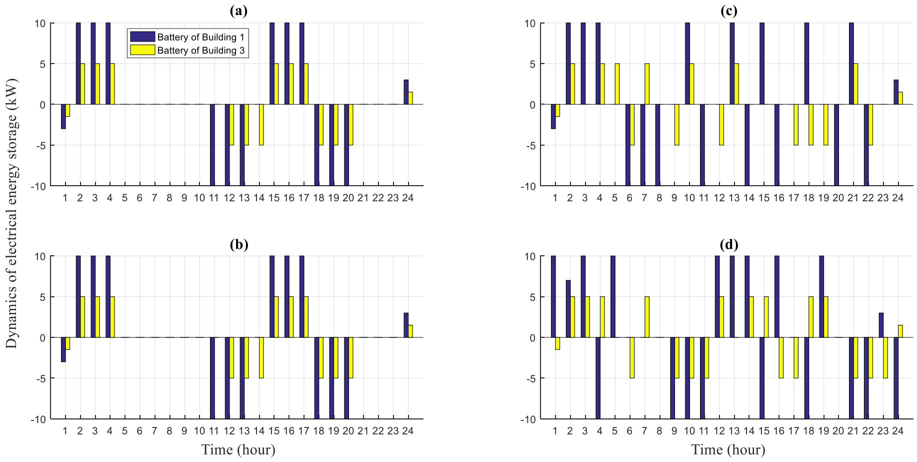

Fig. 4. Dynamics of battery storages under the cases: (a) normal and deterministic, (b) normal and robust, (c) faulty and deterministic, (d) faulty and robust.

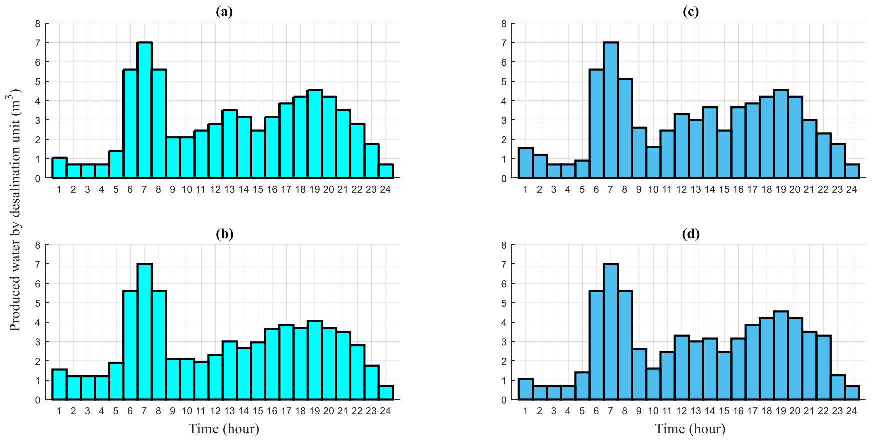

Fig. 5. Desalination unit operation under the cases: (a) normal and deterministic, (b) normal and robust, (c) faulty and deterministic, (d) faulty and robust.

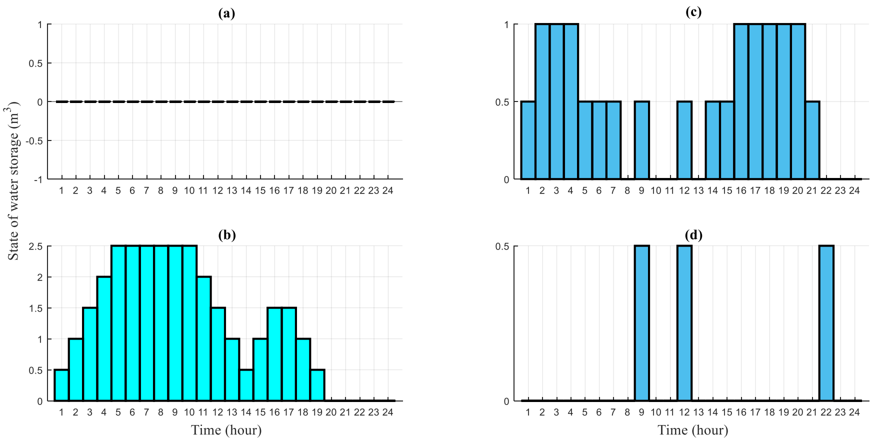

Fig. 6. Water storage state under the cases: (a) normal and deterministic, (b) normal and robust, (c) faulty and deterministic, (d) faulty and robust.

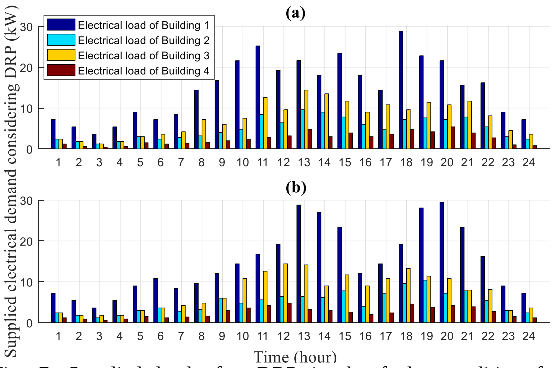

Fig. 7. Supplied load after DRP in the faulty condition for: (a) deterministic case with forecasted solar and wind generation, (b) robust case with considering the full budget of uncertainty for renewable generation.

TABLE II. COMPARISON OF THE TOTAL ENERGY COST OF THE COMPLEX

Γ	Normal condition	Faulty condition	Cost deviation
0	$129.754	$198.075	52.6%
0.2	$132.487	$210.699	59.0%
0.4	$135.287	$218.187	61.2%
0.6	$137.226	$221.853	61.7%
0.8	$138.014	$223.221	61.7%
1	$138.283	$223.725	61.8%

It should be noted the reported analysis are consistent with the risk-neutral (Γ=0) and risk-averse (Γ=1) cases. Due to the insignificant capacity share of renewables in the complex, the cost is only affected by the robust strategy in the first steps. The cost under normal operation is caused by energy exchange with grid and DG production, while the cost of the faulty condition is directly charged by DG generators. By increasing the robustness controlling parameter, the total cost is increased since more uncertainty effects are involved and the energy management gets robust against losses would be incurred without considering these effects. From Table II, the transition from normal to faulty condition imposes at least 53% more cost. It is interesting that under a risk-averse strategy, the cost increment is 62%.

IV. CONCLUSION

In this paper, a resiliency-oriented energy-water management system is developed for a complex with four smart buildings that are empowered by various energy resources, storage systems and desalination units for pure water production. The problem is modeled as an optimization problem which is relied on robust counterparts in order to manage the uncertainty effects caused by integrated renewable resources. The complex is tested under two operative conditions, namely, normal and faulty situations. Under normal conditions the grid connection is available to exchange the energy between each building and the utility grid. However, under faulty conditions, the grid connection is lost and the buildings are connected together using normally-open circuit breakers to create an integrated energy spot in terms of SOS to pool their resources to increase the efficiency, functionality, and resiliency. Under both operative conditions, the energy resources are scheduled for different levels of risk acceptance. The results indicated different scheduling plans for the DGs, desalination, and water storage systems. It is notable that under faulty conditions, time-of-use demand-side management is taken into account to increase flexibility and reduce costs. The comparison of energy scheduling costs showed that there is leastwise a 52.6% increase in the operation cost while the complex shifts from normal to faulty condition. Nonetheless, the cost increment is 61.8% under the risk-averse strategy.

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