# Economic Profit Enhancement of a Demand Response Aggregator Through Investment of Large-scale Energy Storage Systems

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***Abstract*—To provide flexibility for the operation of smart electricity networks, a large number of scattered demand response resources are managed by a demand response aggregator (DRA). Increasing the economic viability of this new entity, i.e., DRA, has attracted a great deal of attention in recent years. Following this direction, this paper proposes stochastic model of multiple large-scale energy storage system (LESS) investments from the perspective of a DRA. A LESS directly connects to smart distribution networks and provides the possibility to save energy costs and thereafter increase the energy efficiency of the DRA. In this paper, a novel mixed-integer model is proposed to determine the optimal capacity and operation of a LESS in coordination with a DR scheme. The model, as a main contribution to literature, comprises novel managerial options, such as the number of allowed DR actions, the number of allowed charging and discharging. Moreover, the model is designed to be capable enough to exclude the hours in which the demand side is not allowed to participate in DR. The proposed model is tested through a numerical example with various case studies. The simulation results show the substantial economic impacts of considering the introduced managerial options in the coordination of a LESS operation with DR.**

***Index Terms*—Demand response, distribution network, energy, energy storage.**

## NOMENCLATURE

### A. Abbreviations

| | |
|---|---|
| DRA | Demand response aggregator. |
| LESS | Large-scale energy storage systems. |
| DR | Demand response. |
| SDN | Smart distribution network. |
| ESS | Energy storage systems. |
| PSB | Polysulfide-bromine battery. |
| VRB | Vanadium Redox battery. |
| ZB | Zinc-Bromine Batteries. |
| MILP | Mixed integer linear programming. |

### B. Parameters

| | |
|---|---|
| $u_{n,s,d}$ | The number of operational days of the nth type of ESS in a year and scenario $s$. |
| $u_{n,s,m}$ | The number of operational months of the nth type of ESS in a year and scenario $s$. |
| $t$ | The number of operation hours of ESS in a day. |
| $ir, dr$ | The inflation rate, Discount rate. |
| $\eta_n$ | The $n$th ESS efficiency (%). |
| $\underline{e}_n, \bar{e}_n$ | Minimum/maximum of $n$th ESS state of energy. |
| $\underline{b}_n^{\text{Char}}, \underline{b}_n^{\text{Dis}}$ | Minimum of charging/discharging of the $n$th ESS. |
| $\bar{b}_n^{\text{Char}}, \bar{b}_n^{\text{Dis}}$ | Maximum of charging/discharging of the $n$th ESS. |
| $\Delta_n$ | The initial energy of the $n$th ESS. |
| $L_{t,s}$ | Total consumed power of SDN at hour $t$ in scenario $s$. |
| $\bar{L}_s$ | Maximum of SDN load in scenario $s$. |
| $\Gamma_s$ | Allowed shiftable load. |
| $\alpha$ | Cut current peak load by energy storage system in percent. |
| $\beta$ | Load demand increase each year in percent. |
| $\Psi_n^{\text{Char}}, \Psi_n^{\text{Dis}}$ | The number of allowed charging/discharging of the $n$th ESS. |
| $\Omega_l, \Omega_m, \Omega_h$ | Purchasing the price of energy from the transmission network, respectively. |
| $\rho_t$ | Price of energy at hour $t$. |
| $C_{n,\text{inv}}$ | Investment cost of upgrading facility. |
| $\Upsilon$ | The number of deferring years. |
| $B^{\text{DE}}$ | Revenue from deferring of facility. |
| $C_n^{\text{P}}, C_n^{W}$ | Peak/energy specific cost of the nth ESS. |
| $C_n^{\text{MF}}, C_n^{\text{MV}}$ | Constant and variable operation and maintenance cost of the $n$th ESS. |
| $\tilde{b}_n^{\text{Dis}}$ | Average annual discharge of $i$th ESS.. |
| $\theta$ | The number of allowed DR hours. |
| $\breve{\eta}_s$ | Percentage of shiftable load in scenario $s$. |
| $\pi_s$ | Probability of scenario $s$. |
| $\Delta\tau$ | Dispatch interval (1-hour). |

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### C. Variables

| | |
|---|---|
| $B_{n,t}^{\mathrm{PR}}$ | Energy price arbitrage benefit of $n$th ESS in hour $t$. |
| $B_{n}^{\mathrm{TR}}$ | The benefit due to the transmission access cost reduction. |
| $b_{n,t}^{\mathrm{Char}}, b_{n,t}^{\mathrm{Dis}}$ | Charging/discharging of the $n$th ESS in hour $t$. |
| $C$ | Objective function. |
| $e_{t,n}$ | The existing amount of energy in the $n$th LESS in $t$th hour. |
| $\tilde{L}_t$ | The load at $t$th hour after implementing demand response program. |
| $C_n^{\mathrm{ESS}}$ | Investment cost of the $n$th ESS. |
| $C_n^{\mathrm{OM}}$ | Operation and maintenance cost of the $n$th ESS. |

### D. Binary Variables

| | |
|---|---|
| $z_{n,t}$ | Binary variable corresponding to the $n$th ESS at hour $t$ in scenario $s$. |
| $\lambda_t$ | Binary variable corresponding to the demand response program in scenario $s$. |

### E. Sets

| | |
|---|---|
| $N$ | The sets of LESSs. |
| $T$ | The set of hours in a day. |
| $T_{na}$ | The set of hours in a day in which demand response is not allowed $T_{na} \subset T$. |
| S | set of scenarios. |

## I. Introduction

### A. Problem Statement

URBANIZATION creates several challenges for governments throughout the world. These challenges include air pollution, congestion, crime, human health, and energy [1], [2]. In recent years, through the enjoyment from the development of ICT and other related technologies and sustainable energy resources, the concept of a sustainable city in comparison to a regular city, has emerged to effectively tackle the aforementioned challenges to enhance the operational efficacy of urban services, as well as the quality of life [3]. Thanks to the development of ICT technologies in sustainable cities, DR schemes can be effectively developed to increase energy efficiency [4], [5]. The emergence of a new entity called "demand response aggregator" (DRA) as a result of increasing penetration of a large amount of scattered DR resources brings new hope to accumulating the positive effects of DR in a larger scale of energy services. The increasing economic effectiveness of DRA is an important problem that needs to be taken into consideration. This paper proposes the investment of a Large-scale energy storage system (LESS) by the DRA to increase its economic profit.

### B. Literature Review

Despite the profit increasing from DRA using energy storage systems (ESS) as discussed in recent literature, such as [6], [7], there is a lack of enough attention to the investment of ESS, specially LESS, from the perspective of DRA. In [6], [7], it is assumed that a DRA owns a set of storage systems and the profit of DRA is maximized by selling the stored energy. In [6], a networked cournot competition graph has been proposed for the sake of competition among DRAs. In [7], an incomplete game-theoretical model for the competition between DRAs in selling energy previously stored in an aggregation of storage devices, given sufficient demand from other aggregators through an incomplete information game, was proposed.

Generally, the proliferation of energy storage systems (ESS) in sustainable cities is highly mobilized, as a result of a few serious challenges, which are primarily related to economic issues [8], security concerns [9], and environmental problems [10], forced by several reasons, such as significant growth in demand for electrical energy, resiliency challenges as a result of global warming, risk of terrorist attacks to the electricity network infrastructure, meeting the target of $CO_2$ emission reduction in the electricity sector, and thereafter increasing the share of intermittent renewable resources. According to the International Energy Agency, globally installed ESS capacity should be approximately 3.2 times higher in 2050 in comparison to that of 2014 to limit global warming to below 2°C [11]. To meet this environmental-driven requirement, ESS should be optimally integrated into the power systems. Optimal grid integration of ESS creates numerous benefits, including power fluctuation smoothing [12], effective operation of power systems with high penetration of renewable resources [13], optimizing the energy transaction costs [14], and peak load shaving [15]. The transmission of bulk quantities of electrical energy faces new challenges, as transmission components are exposed to failure more than in the past, as a consequence of global warming [16], and degradation of transmission facilities. Moreover, the lack of enough capacity in transmission lines results in congestion [17], [18]. As an energy solution for sustainable cities, the integration of large-scale ESS (LESS) to distribution substations can ensure smart distribution network (SDN) operations against these problems. As a result, the energy efficiency of the sustainable city can be increased.

In simple words, the ESS is managed so that it stores the excess of electrical energy, from tens to hundreds of MWh, during a low-cost period of time, and then releases it during a proper time when SDN operators economically or physically face limitations for getting energy from the transmission system. Though the grid integration of ESS became feasible technologically [19], the investment cost of these devices is still high [20]. To enhance the economic profit, in this paper, a mixed integer model is developed to provide the optimal capacity and operations of LESS coordinated with demand response (DR) in a sustainable city. DR enables the sustainable city's residents to actively participate in the operation of SDN [21]. An extensive amount of literature has been dedicated to the applications of ESS in SDN [22]–[37]. Some of the technical advantages for the installation of ESS in SDN include differing distribution lines' upgrading, tackling load balancing problems due to increasing the share of intermittent renewable resources, ensuring energy security, improving stability and power quality, and increasing the penetration of distributed generation [25]. To achieve maximum benefit exploitation from ESS integration, determining the optimal capacity and operation of these flexible devices is necessary. In [22], optimal capacity, location, and power rating of batteries throughout the distribution network was obtained by minimizing investment, operations, and reliability costs subject to technical constraints. Other approaches for reliability enhancement by means of ESS planning are addressed in [27], [28]. Beyond these scientific studies, the application of ESS for reliability improvement of a real case study in a Chilean power system was reported in [30]. In [23], improvement of the load and distributed generation hosting ability of the utility grid was considered as the objective for the battery location in SDN. The positive impacts of proper charging and discharging of battery ESS on transient stability, see [32], and voltage deviation, see [33], was proved. The impact of various battery technologies in the optimal planning of ESS was observed in [24]. Further to the mentioned literature in which technical and economic objectives have been considered in the planning of ESS in SDN, some other research studies addressed the interaction of ESS planning with other effective factors, such as power demands of electrical vehicles [31]. Also, distribution network expansion affects optimal ESS location and vice versa [25], [26]. Due to the high investment costs of ESS, in [28] some technical constraints, such as state of health and the maximum number of charging and discharging to preserve the ESS lifetime, are considered. These constraints limit the maximum benefit extraction from the ESS integration. Also, according to a recent review on the optimal planning of ESS [30], justification of economic benefits of ESS is a challenge that needs to be addressed.

To enhance the economic viability of DR programs, coordination of DR and ESS was proposed as a solution. Generally, in DR schemes, customers are motivated to play a more effective role through load shifting [38]. Implementation of a DR program postpones network reinforcement costs of energy systems [39]. Coordination of DR and ESS operations was addressed in a few previous studies, such as [34]. However, the advantages of this coordination should be further investigated. To the best of our knowledge, the advantages brought from the coordination of LESS planning and DR aggregation were not explored in literature in spite of the real application of LESS in different countries [40]. Furthermore, there are just a few studies in literature dedicated to the optimal capacity and operation of LESS connected to the distribution substation [19], [41]. In [19], an economic analysis model was developed for LESS. The proposed model is non-linear and it was solved by a genetic algorithm. The investment cost of the LESS is high. However, the proposed model is not flexible enough to consider the number of allowed charging/discharging for the LESS to guarantee the health of LESS. In [41], by deploying an evolutionary multi-objective approach, potential benefits of installation of Polysulfide-bromine (PSB) and Vanadium Redox (VRB) battery technologies in distribution substations were investigated. The presented method is not convex. Therefore, achieving the optimal solution cannot be guaranteed. Also, capability of demand response was not considered in the proposed approach. In [42], was proposed an energy management and operational control methods for grid battery energy storage systems. In [43], an efficient decomposition method for bilevel energy storage arbitrage problem was proposed.

Table I compares the features of this paper in comparison to other papers that focused on DRA. The other lines of papers, such as [12]–[14], [19], and [22], consider LESS, but DR is not included in the optimization model.

TABLE I
TAXONOMY TABLE

| Reference | LESS | Stochastic model | DRA | The number of allowed DR actions | The number of allowed charging and discharging of LESS |
|---|---|---|---|---|---|
| [7] | – | – | ✓ | – | – |
| [12] | ✓ | ✓ | – | – | – |
| [13] | ✓ | ✓ | – | – | – |
| [14] | ✓ | ✓ | – | – | – |
| [19] | ✓ | – | – | – | – |
| [22] | ✓ | ✓ | – | – | – |
| [44] | ✓ | – | ✓ | ✓ | – |
| [45] | ✓ | ✓ | ✓ | – | – |
| [46] | ✓ | – | ✓ | ✓ | – |
| [47] | ✓ | – | ✓ | – | – |
| This study | ✓ | ✓ | ✓ | ✓ | ✓ |

### C. Contributions and Organization

To the best of our knowledge, for the first time, this paper proposes stochastice MILP economic profit enhancement of DRA by integration of a LESS into the distribution substation. Moreover, the proposed MILP framework provides a more precise model which benefits from two additional novelties: First, the number of allowed DR actions, excluding emergency hours without the cooperation of DR, is included in the proposed stochastice model. Second, the number of allowed charging and discharging of LESS is considered. The effectiveness of the modeling considerations is evaluated in a case study. To provide a more realistic model, we replicate load uncertainties by producing a set of proper scenarios.

The organization of this paper is as follows: After provisioning of the introduction in Section I, the proposed mathematical model is provided in Section II. Section III is devoted to the numerical case study. Finally, Section IV concludes the paper.

## II. MATHEMATICAL MODEL

The objective function is presented as:

$$\max \sum_{s\in S} \pi_s(\tau + \upsilon + B_n{}^{\mathrm{DE}} - \omega - \xi) \quad \forall n \in N, t \in T \tag{1a}$$

$$\tau = \sum_{n\in N}\sum_{t\in T}\sum_{s\in S} B_{n,t}^{\mathrm{PR}} u_{n,d,s} \left(\frac{1+ir}{1+dr}\right)^{\mathrm{t}} \quad \forall n \in N, t \in T, s \in S \tag{1b}$$

$$\upsilon = \sum_{n\in N}\sum_{t\in T}\sum_{s\in S} B_{n}^{\mathrm{TR}} u_{n,s,m} \left(\frac{1+ir}{1+dr}\right)^{\mathrm{t}} \quad \forall n \in N, t \in T, s \in S \tag{1c}$$

$$\omega = \sum_{n\in N} C_n^{\mathrm{ESS}} \quad \forall n \in N \xi = \sum_{n\in N}\sum_{t\in T}\sum_{s\in S} C_{n,}^{\mathrm{OM}} u_{n,m} \left(\frac{1+ir}{1+dr}\right)^{\mathrm{t}} \tag{1d}$$

$$\forall n \in N, t \in T, s \in S \tag{1e}$$

Equation (1) consists of five terms including three benefit oriented terms, and two cost oriented terms [19]. In (1a), $\tau$ is the profit of energy trading of DRA, $\upsilon$ is the profit from transmission access cost reduction, and $B^{\text{DE}}$ is the profit from deferring facility investment through LESS. These mentioned terms are benefit-oriented. Also, the cost-oriented terms are as follows: $\omega$ is the LESS investment cost, and $\xi$ is the operation and maintenance cost of the LESS. The aim of the proposed problem is to maximize the monetary objective function (1) subject to a set of technical and economic constraints (2)–(14).

Equation (2) shows the balancing between charging and discharging of each battery for all operating hours in a day by considering the respective LESS efficiency:

$$\sum_{t\in T} b_{n,t}^{\text{DIS}} - \sum_{t\in T} b_{n,t}^{\text{CHAR}} \eta_n = 0 \quad \forall n \in N, t \in T \tag{2}$$

where $b_{n,t,s}^{\text{DIS}}$ and $b_{n,t,s}^{\text{CHAR}}$ are discharging/charging of the nth ESS in hour t in scenario $s$. Eq. (3) guarantees the limitation for discharge power for each LESS by considering the amount of energy in each LESS.

$$\sum_{t\in T} b_{n,t}^{\text{Dis}} \leq \sum_{t\in T} e_{n,t} \quad \forall n \in N, t \in T \tag{3}$$

Equations (4) and (5) guarantee the discharging/charging power to be less than or equal to the discharge/charging rate, respectively.

$$\bar{b}_n^{\text{Dis}}(1 - z_{n,t}) \geq b_{n,t}^{\text{Dis}} \geq \underline{b}_n^{\text{Dis}} \quad \forall n \in N, t \in T, z_{n,t} \in \{0,1\} \tag{4}$$

$$\bar{b}_n^{\text{Char}} z_{n,t} \geq b_{n,t}^{\text{Char}} \geq \underline{b}_n^{\text{Char}} \quad \forall n \in N, t \in T, z_{n,t} \in \{0,1\} \tag{5}$$

Each LESS's state of energy in $t+1$ is shown through a difference equation in (6):

$$e_{t+1,n} = e_{t,n} + (b_{t+1,n}^{\text{Char}} - b_{t+1,n}^{\text{Dis}})\Delta\tau \quad \forall n \in N, t \in T \tag{6}$$

where $e_{t,n,s}$ is the amount of energy in the $n$th LESS in the $t$th hour in scenario $s$. The initial state for the expressed difference equation (6) is shown in (7).

$$e_{t,n} = \Delta_n + b_{t,n}^{\text{Char}} - b_{t,n}^{\text{Dis}} \quad \forall n \in N, t = 1 \tag{7}$$

The limitation of energy for each of the LESS energy in hour $t$ is shown in (8).

$$\underline{e}_n \leq e_{n,t} \leq \bar{e}_n \quad \forall n \in N, t \in T \tag{8}$$

Equation (9) limits the load at the $t$th hour based on allowed shiftable consumed load ($\Gamma$):

$$\begin{aligned} &\tilde{L}_{t,s} \leq L_{t,s} + \Gamma_s \lambda_{t,s}, \tilde{L}_{t,s} \geq L_{t,s} - \Gamma_s \lambda_{t,s} \\ &\forall t \in T,\ s \in S, \lambda_{t,s} \in \{0,1\} \end{aligned} \tag{9}$$

Based on (9), if demand response is not performed at the $t$th hour, then $\tilde{L}_t = L_t$. If demand response is not performed at the $t$th hour, then $\tilde{L}_t$ obtains a value in the interval of $[L_t - \Gamma \quad L_t + \Gamma]$. The parameter $\Gamma$, i.e., the amount of allowed shiftable load, is determined by the DRA based on the type of available loads. For example, if the loads are heating, ventilation, and air conditioning (HVAC) loads, $\Gamma$ depends on the comfort and convenience of the consumers and it will be different case by case.

By applying (10), the DRA is able to limit the number of allowed DR hours. In this equation, the parameter $\theta$ is the number of allowed DR hours. If the DRA set does not allow DR action, $\theta$ is set as zero. Otherwise, since in the load shifting procedure, load is shifted from one hour to another hour in the 24-hour operating period, $\theta$ is not allowed to be 1.

$$\sum_{t\in T} \lambda_t - \theta_s \leq 0, \quad \forall \lambda_t \in \{0,1\} \tag{10}$$

Equation (11) shows that the amount of total demand in 24-hours which remains equal before and after implementing the DR scheme.

$$\sum_{t\in T} \tilde{L}_{t,s} - \sum_{t\in T} L_{t,s} = 0 \quad \forall s \in S \tag{11}$$

Equation (12) imposes another constraint for cutting of the peak load, see [19]. This constraint would be realized by choosing the appropriate amount of $\alpha$. For example, if parameter $\alpha_s$ is set to 0.1, the DR scheme is allowed to shave 10% of the load peak.

$$\tilde{L}_t - b_{n,t}^{\text{Dis}} + b_{n,t}^{\text{Char}} - (1-\alpha)\bar{L}_s \leq 0 \quad \forall n \in N, s \in S, t \in T \tag{12}$$

Equation (13) retains the allowed charging and discharging actions within their limits ($\Psi_{n,s}^{\text{Char}}, \Psi_{n,s}^{\text{Dis}}$). Such imposed limitations usually are determined based on the specification of the LESS type. It is noted that in a specific hour a LESS could only charges or discharge which has been imposed in (4) and (5).

$$\sum_{t\in T} 1 - z_{n,t} \leq \Psi_n^{\text{Dis}}, \sum_{t\in T} z_{n,t} \leq \Psi_n^{\text{Char}} \quad \forall n \in N \tag{13}$$

where $\Psi_{n,s}^{\text{Dis}}$ and $\Psi_{n,s}^{\text{Char}}$ are the number of allowed discharging and charging of the $n$th ESS in scenario $s$. Eq. (14) guarantees that in each hour charging power is less than or equal to the existing amount of energy in each LESS. This proposed mathematical model is capable enough to provide consumers this possibility to exclude any hours in the day from the set of allowed DR periods.

$$b_{n,t}^{\text{Dis}} \leq e_{n,t} \quad \forall n \in N, t \in T \tag{14}$$

For this purpose, (15) is considered as a constraint. In this constraint, $T_{na}$ is the set of hours in a day in which DR is not allowed.

$$\lambda_t = 0 \quad \forall t \in T_{na} \subset T \tag{15}$$

Equations (16)–(20) are expressed to show the used terms in (1) including the profit of energy trading, the profit from transmission access cost reduction, the benefit from deferring facility investment, the LESS investment cost, and the operation and maintenance costs of the LESS.

$$B_n^{\text{PR}} = b_{n,t}^{\text{Dis}} - b_{n,t}^{\text{Char}} \rho_t \forall n \in N, t \in T \tag{16}$$

$$\begin{aligned} B_n^{\text{TR}} = &\left(b_{n,t_{\text{low}}}^{\text{Dis}} - b_{n,t_{\text{low}}}^{\text{Char}}\right)\Omega_{\text{low}} + \left(b_{n,t_{\text{high}}}^{\text{Dis}} - b_{n,t_{\text{high}}}^{\text{Char}}\right)\Omega_{\text{high}} \\ &+ \left(b_{n,t_{\text{med}}}^{\text{Dis}} - b_{n,t_{\text{med}}}^{\text{Char}}\right)\Omega_{\text{med}} \end{aligned}$$

$$\forall n \in N, t_{\text{low}}, t_{\text{high}}, t_{\text{med}} \in T \tag{17}$$

$$B_n{}^{\text{DE}} = C_{n,\text{inv}} \left(1 - \left(\frac{1+ir}{1+dr}\right)^{\Upsilon}\right) \forall n \in N \tag{18}$$

$$C_n^{\text{ESS}} = C_n^{\text{P}} \max(b_n^{\text{Char}} + b_n^{\text{Dis}}) + C_n^{W} \max(e_n)$$
$$\forall n \in N \tag{19}$$

$$C_n^{\text{OM}} = C_n^{\text{MF}} \max(b_n^{\text{Char}} + b_n^{\text{Dis}}) + C_n^{\text{MC}} \tilde{b}_n^{\text{Dis}}$$
$$\forall n \in N \tag{20}$$

The deferring year and total shiftable consumed power are shown in (21) and (22), respectively.

$$\Upsilon = \frac{\log(1+\alpha)}{\log(1+\beta)} \tag{21}$$

$$\Gamma_{t,s} = \breve{\eta} L_{t,s} \quad \forall t \in T, s \in S \tag{22}$$

It is noted that in this optimization model, the decision variables are $b_{n,t,s}^{\text{Char}}, b_{n,t,s}^{\text{Dis}}, e_{n,t,s}, \tilde{L}_{t,s}, z_{n,t,s}, \lambda_{t,s}$.

## III. Numerical Example

In this section, a case study is presented and the proposed mathematical model is solved and the results are analyzed. The price and load data have been obtained from [19] which corresponds to the modified values from the New York Independent System Operator (ISO). The applied LESS types include the Vanadium Redox Battery (VRB), Polysulfide-Bromine Batteries (PSB), and Zinc-Bromine Batteries (ZB). The storage data is given in [41]. The DRA may have this possibility to employ one or more than one LESS technologies. Without loss of generality, in subsection $A$, we apply the proposed model for VRB technology as the first investment scenario. In subsection $B$, a more complex investment scenario is introduced by employing three types of LESS technologies (VRB, PSB, and ZB). Fig. 1 shows a simplified decision-making procedure by the DRA. The maximum peak value for the load is 22 MW and 65 MW for the two investment scenarios, respectively. The average of the seasonal load profile is shown in Fig. 2.

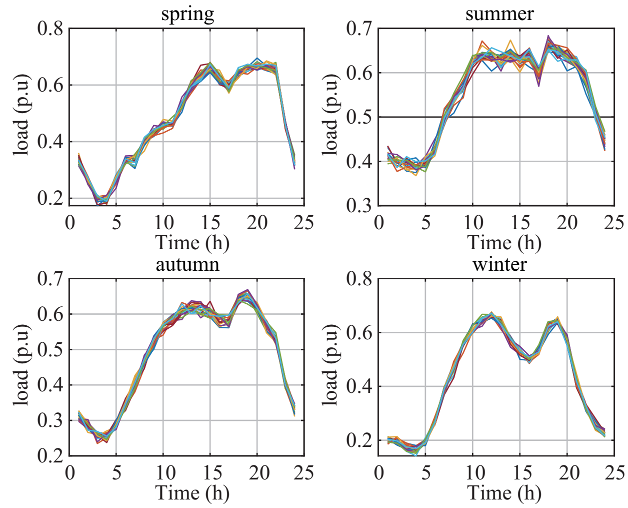


Fig. 2. Twenty scenarios for hourly seasonal load profiles.

In both investment scenarios, the Normal distribution is considered to generate a set of load scenarios for modeling stochasticity. All simulations are performed using MATLAB 2018b and Gurobi 9 commercial solver on a 1.8 GHz computer with 6 GB of RAM.

### A. A Single-type LESS

To show the results for the single-type LESS, it is assumed that a VRB LESS with 75% efficiency is connected to the distribution substation. The results are analyzed for the following four cases:

Case 1) The number of allowed DR actions and charging and discharging of LESS are not considered.

Case 2) The number of allowed charging/discharging of LESS is considered ($\Psi_{n,s}^{\text{Dis}} = 5$).

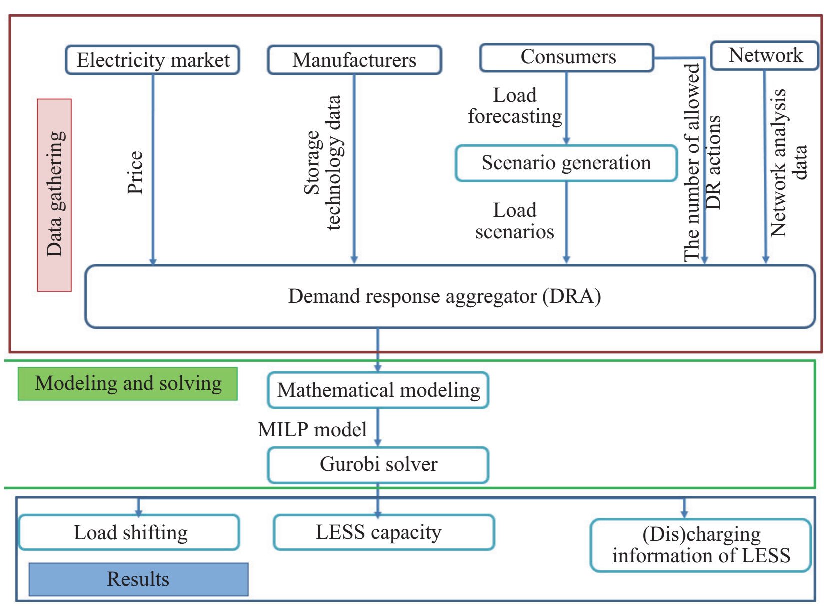


Fig. 1. The decision-making procedure of DRA.

Case 3) The number of allowed DR actions is considered ($\theta_s = 10$). Also, load shifting is not allowed in hours 18 and 19 ($\lambda_{18,s} = \lambda_{19,s} = 0$).

Case 4) The assumptions of cases 2 and 3 are considered altogether.

It should be noted that the load profile is the same for all cases. As shown in Fig. 2, for each hourly seasonal load, 20 scenarios are considered, i.e., the cardinality of S is 20. Also, the percentage of shiftable load ($\breve{\eta}_s$) is 10%. Table II shows the results of solving the proposed optimization model (Eqs. (1)–(22)) for all the above cases. It is observed that in all the cases 1–4, in which LESS is installed, the profit of DRA from the demand response program increased 20.7, 17.1, 18.44, and 13.8 times compared to the case without LESS respectively. This shows the economical effectiveness of the proposed approach to increase the revenue of the DRA from the demand response program. Also, it is shown in Table II, by considering the number of allowed charging/discharging of LESS and the number of allowed DR actions (case 4), the investment cost has been reduced. However, due to the additional limitations imposed on the model, the total objective function is reduced. As noted, we have about 1.97 M$/year decrease in the objective function value through the comparison of cases 1 and 4. This point shows that the technical limitations of LESS and the demand response program can greatly affect the profits obtained by the DRA. Also, comparisons of Case 1 and Cases 2–4 show that considering the limitations pertaining to LESS and demand response further decreases the capacity of LESS. These results highlight the importance of additional consideration pertaining to the number of allowed DR actions, and the number of allowed charging and discharging of LESS that have to be precisely modeled in the proposed optimization framework.

TABLE II
THE INVESTMENT RESULTS OF SINGLE-TYPE LESS INVESTMENT SCENARIO

| Description | Without LESS | Case 1 | Case 2 | Case 3 | Case 4 |
|---|---|---|---|---|---|
| LESS investment cost (M$) | 0 | 8.85 | 8.17 | 7.66 | 6.58 |
| LESS operation cost (M$/year) | 0 | 0.75 | 0.84 | 0.65 | 0.66 |
| LESS energy trading profit (M$/year) | 0 | 8.21 | 7.32 | 7.27 | 5.73 |
| Demand response profit (M$/year) | 0.27 | 5.59 | 4.62 | 4.98 | 3.73 |
| The Objective Function (M$/year) | 0.27 | 3.92 | 2.67 | 3.69 | 1.95 |
| LESS Capacity (MW) | 0 | 57 | 46 | 49 | 38 |
| Discharge peak (MW·h) | 0 | 8 | 9 | 7 | 7 |
| Charge peak (MW·h) | 0 | 8 | 8 | 7 | 7 |

In case 1, the investment cost is 8.85 M$ and the annual profit would be $8.21 + 5.59 - 0.75 = 13.05$ M$/year. Therefore, by considering most of the usual interest rates, for example from 0.25% to 30%, the payback period would be less than 1 year. Also, in case 4, the investment cost is 6.58 M$ and the annual profit would be $5.73 + 3.73 - 0.66 = 8.8$ M$/year. In this case, the payback period would be less than 1 year for most of the usual interest rates as well. If there is an investment budget limitation by DRA, an option for LESS investment is a joint venture which is out of the scope of this paper and can be addressed in future studies. Fig. 3 shows a comparison between the daily average of the load profile in the initial state (red line) and after implementing cases 1–4 (blue line) by allowing 10% of the load shifting. In case 1, the results depicted in Fig. 3 show that the demand response program adopted by the DRA reduces the peak. Cases 3 and 4 show that the load at hours 18 and 19 have not changed. This verifies the results because load shifting is not allowed in these hours ($\lambda_{18,s} = \lambda_{19,s} = 0$).

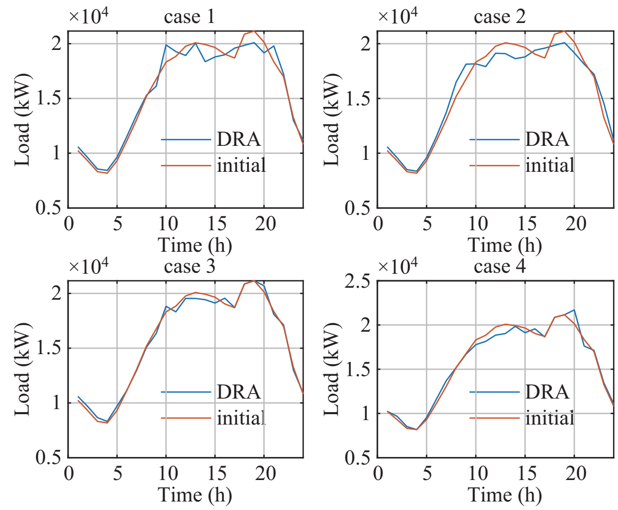


Fig. 3. The daily average of the load profile in the initial state (red line) and after implementing the case studies (blue line) for the single-type investment scenario.

Also, more results on the state of energy and charge of the LESS in cases 1–4 are shown in Figs. 4 and 5, respectively.

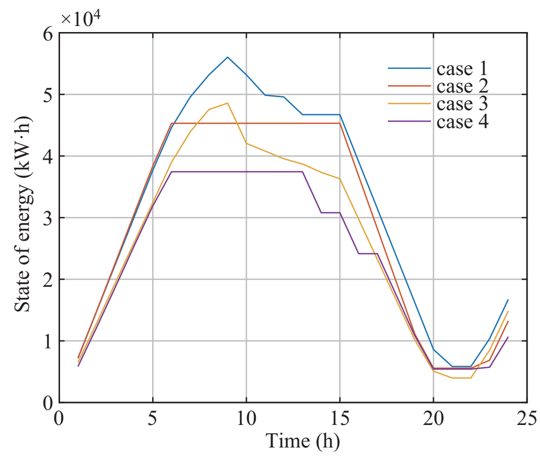


Fig. 4. The state of energy for cases 1–4 for the single-type investment scenario.

*B. A Multi-type LESS*

In this subsection, a more complex investment scenario is introduced by employing three types of LESS technologies (VRB, PSB, and ZB). The storage technologies are referred

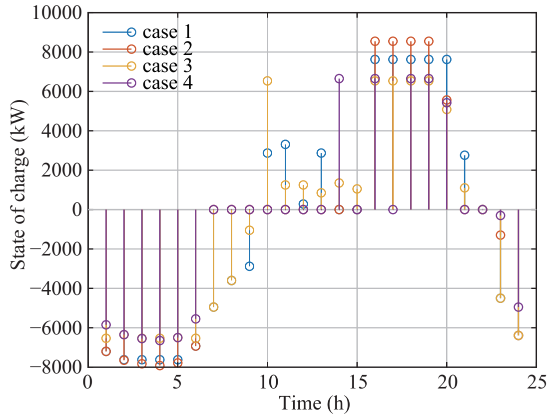


Fig. 5. The state of charge for cases 1–4 for the single-type investment scenario.

to in [41]. The storage efficiency of all technologies is 75% and the peak maximum is 65 MW.

The comparison of Tables II and III shows that the objective functions of the cases in Table III are higher than that of Table II. This shows that if DRA has multiple options to select the technology, it ensures that the revenue increases. It is noted that the CPU time for solving the single-type LESS is 0.8 s for all cases. However, the CPU time for the multi-type LESS significantly increases. By considering case 4 in both investment scenarios (single and multi-type LESS), the CPU time increase from 0.8 s to 8,520 s.

For the multi-type investment scenario, the average of the load profile is depicted in Fig. 6. Also, Figs. 7–8 show the state of energy and charge for cases 1–4, respectively. Tables IV and V show the number of variables and constraints for both investment scenarios of single-type and multi-type LESS.

TABLE III
THE INVESTMENT RESULTS OF MULTI-TYPE LESS INVESTMENT SCENARIO

| Description | Case 1 | Case 2 | Case 3 | Case 4 |
|---|---|---|---|---|
| LESS investment cost (M$) | 25 | 24.24 | 22.74 | 21.97 |
| LESS operation cost (M$/year) | 2.3 | 2.47 | 1.94 | 2.58 |
| LESS energy trading profit (M$/year) | 24.56 | 21.78 | 21.78 | 21.75 |
| Demand response profit (M$/year) | 15.48 | 13.73 | 14.79 | 10.76 |
| The Objective Function (M$/year) | 12.47 | 8.53 | 11.62 | 7.7 |
| LESS Capacity (MW) | 150, 5, 17 | 136 | 144, 3 | 106, 13, 20 |
| Discharge peak (MW·h) | 20, 2, 3.1 | 25 | 20, 0.5 | 20, 26, 4 |
| Charge peak (MW·h) | 19.1, 1.2, 3.1 | 24 | 20, 0.5 | 19, 3, 4 |
| CPU time (sec) | 4 | 430 | 5 | 8520 |

TABLE IV
THE NUMBER OF VARIABLES AND CONSTRAINTS FOR SINGLE-TYPE LESS

| Number of load scenario | Variables | | Constraint | |
|---|---|---|---|---|
| | case 1 | case 4 | case 1 | case 4 |
| 5 | 868 | 1139 | 558 | 837 |
| 20 | 2668 | 3674 | 1653 | 2667 |
| 50 | 6268 | 8744 | 3843 | 6327 |
| 100 | 12268 | 17194 | 7493 | 12427 |
| 200 | 24268 | 34094 | 14793 | 24627 |

TABLE V
THE NUMBER OF VARIABLES AND CONSTRAINTS FOR MULTI-TYPE LESS

| Number of load scenario | Variables | | Constraint | |
|---|---|---|---|---|
| | case 1 | case 4 | case 1 | case 4 |
| 5 | 1404 | 1679 | 944 | 1227 |
| 20 | 3204 | 4214 | 2039 | 3057 |
| 50 | 6804 | 9284 | 4229 | 6717 |
| 100 | 12804 | 17734 | 7879 | 12817 |
| 200 | 24808 | 34636 | 15179 | 25017 |

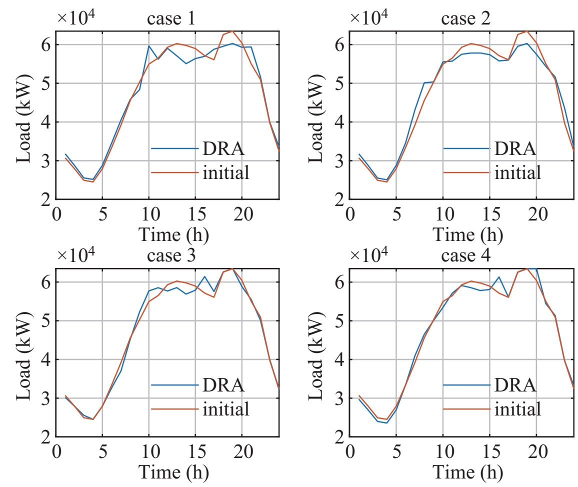


Fig. 6. The daily average of the load profile in the initial state (red line) and after implementing the case studies (blue line) for the multi-type investment scenario.

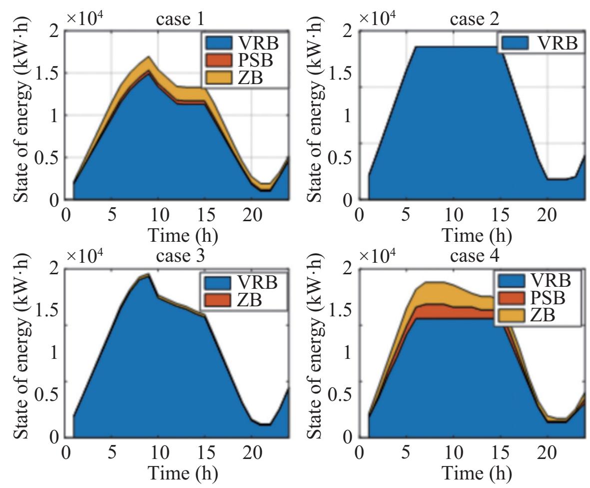


Fig. 7. The state of energy for cases 1–4 for the multi-type. investment scenario.

The results show that the number of constraints and variables increases when more scenarios are considered for the load profile. Also, the number of constraints and variables in the scenario of multi-type LESS is higher than that of single-type LESS.

## IV. CONCLUSION

In this paper, as a stochastic cost-effective approach for energy management of sustainable cities, a novel coordination of LESS optimal operations and DRA is addressed by

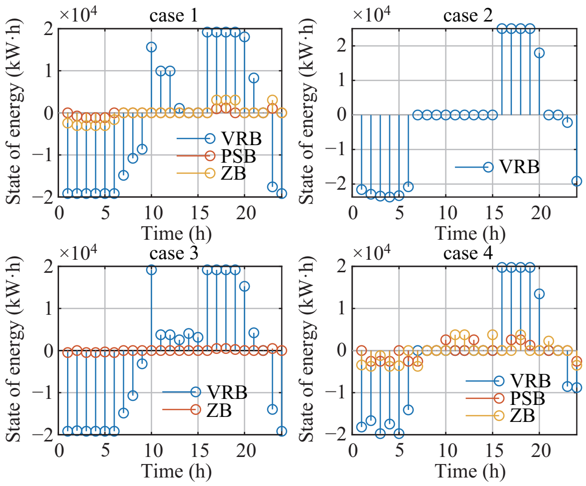


Fig. 8. The state of charge for cases 1–4 for the multi-type investment scenario.

considering managerial options for LESS and DRA. For this purpose, a mixed-integer mathematical model is proposed which is able to obtain the optimal capacity of LESS and demand modifications. The proposed model enjoys several advantages, such as being shiftable enough to include the number of allowed DRA actions, and the number of allowed charges and discharges, further excluding emergency hours without the cooperation of DRA. Moreover, the model is mixed-integer linear which yields the exact optimal solution though solving by well-developed optimization packages. To verify the effectiveness of the proposed method, a numerical study with 5 different case studies was examined. The results show that coordination of LESS operations with DRA results in greater total benefits for the smart distribution network operator in comparison with the scenario in which just LESS operations are considered.

The analysis of the results shows that this economic effectiveness is affected by the considered DRA and LESS operational limitations, such as off-hours, the number of allowed DRA hours, the percentage of load shaving, and the number of allowed discharging. It was observed that LESS operational limitations decrease the economic benefits of the proposed coordination scheme. However, such limitations provides increased safety and a longer LESS lifetime. Moreover, simulation results show that the number of allowed discharges would highly affect the number of operated LESSs. In future stusies, a trade-off between LESS lifetime and economic benefits should be performed in a more quantitative form. In this paper, we consider LESS connected to a distribution substation. In a future study, the proposed model is developed for a number of distribution substations connected to various sustainable cities with different desired flexibilities of DR. Also, in addition to LESS, the DRA may involve a wind farm. The relevant techno-economic analysis can be made in future research.

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