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Optimal Scheduling of Electrical Storage System and Flexible Loads to Participate in Energy and Flexible Ramping Product Markets

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Abstract- *The power systems operation has encountered some challenges due to the increasing penetration rate of renewable energy sources. One of the main challenges is the intermittency of these resources, which causes power balance violations. On the other hand, there are various distributed energy resources (DERs) to compensate for the need for the ramp capacity. Hence, to indicate this issue, the energy storage systems and the heating, ventilation, and air conditioning (HVAC) loads are selected in the form of a DER aggregator (DERA) to participate in the day-ahead (DA) energy and flexible ramping product (FRP) markets in this paper. Therefore, a co-optimization method is used to model the aggregator's decision-making, as a mixed-integer linear programming (MILP) approach, in both the markets. The obtained results revealed that the profit of the DERA increases by considering not only its participation in the joint energy and FRP markets but also the potential of the HVAC loads. Moreover, the accuracy of the model is investigated using the sensitivity analysis of the parameters, including deployment probability, customers' welfare, and the allowed temperature deviation.*

Keyword: Day-ahead energy market; Flexible ramping product; Aggregator; HVAC; Electrical energy storage systems.

NOMENCLATURE

Nomenclature

Abbreviations

CHP	Combined heat and power
DG	Distributed generation
DER	Distributed energy resource
DERA	DER aggregator
DA	Day-ahead
DR	Demand response
ESS	Electrical storage system
ESSA	ESS aggregator
EV	Electric vehicle
FRP	Flexible ramping product
HVAC	Heating, ventilation, and air conditioning
PV	Photovoltaic
PEV	Plug-in electric vehicle
RES	Renewable energy source
RT	Real-time

Indices

j	Index of ESSs
h	Index of houses
t	Index of time periods

Parameters

$\overline{DB}_h/\underline{DB}_h$	The allowed up/down deviation of indoor temperatures from the desired temperature of house h
k_{cw}	Customers welfare coefficient
k_1, k_2, k_3, k_4	Thermal equation coefficients
ΔT	Time granularity
M_h	Mass of air in household h
C_a	Thermal capacity of air
R_h^{eq}	Thermal resistance of household h
COP_h^{AC}/COP_h^{H}	Coefficient of cooling/heating performance of HVAC in house h
$P_h^{\max\_AC}/P_h^{\max\_H}$	Maximum cooling/heating power of HVAC of house h
$P_j^{\max\_ch}/P_j^{\max\_dch}$	Maximum charging/discharging power of ESS j
SOE_j^{max}/SOE_j^{min}	Maximum/minimum energy state of ESS j
T_t^a	Ambient temperature in period t
$T_{t,h}^{des}$	User-selected temperature in period t in house h
λ_t^{DA}	DA energy market price in period t
λ_t^{RT}	RT energy market price in period t
β	Demand price of FRP
π_t^{up}/π_t^{dn}	Acceptance probability of up/down FRP d in period t

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Research Paper

ρ_t^{up}/ρ_t^{dn}	Deployment probability of up/down FRP in period t
η_j^{ch}/η_j^{dch}	Charging/discharging efficiency of the ESS connected to MG j

Variables

R_{en}	The total DA cost
C_{cw}	The total cost of deviation of indoor temperatures from desired temperatures
P_t	DA power exchange in period t
$P_{t,h}^{FL}$	Demand of flexible load h in period t
$\overline{P}_{t,h}^{FL}/\underline{P}_{t,h}^{FL}$	The maximum/minimum possible demand for flexible load h in period t
$P_{t,h}^{AC}$	Cooling power consumption of HVAC of house h in period t
$\overline{P}_{t,h}^{AC}/\underline{P}_{t,h}^{AC}$	The maximum/minimum possible cooling power consumption of HVAC of house h in period t
$P_{t,h}^{H}$	Heating power consumption of HVAC of house h in period t
$\overline{P}_{t,h}^{H}/\underline{P}_{t,h}^{H}$	The maximum/minimum possible heating power consumption of HVAC of house h in period t
$P_{t,j}^{ESS}$	Power of ESS j in period t
$\overline{P}_{t,j}^{ESS}/\underline{P}_{t,j}^{ESS}$	The maximum/minimum possible power of ESS j in period t
$P_{t,j}^{ch}$	Charging power of ESS j in period t
$\overline{P}_{t,j}^{ch}/\underline{P}_{t,j}^{ch}$	The maximum/minimum possible charging power consumption of ESS j in period t
$P_{t,j}^{dch}$	Discharging power of ESS j in period t
$\overline{P}_{t,j}^{dch}/\underline{P}_{t,j}^{dch}$	The maximum/minimum possible discharging power of ESS j in period t
R_{ra}	The total revenue of providing FRP
Rup_t/Rdn_t	The total ramp-up/down FRP in period t
$Rup_{t,h}^{FL}/Rdn_{t,h}^{FL}$	The ramp-up/down FRP of flexible load Hin period t
$Rup_{t,j}^{ESS}/Rdn_{t,j}^{ESS}$	The ramp-up/down FRP of ESS j in period t
$SOE_{t,j}$	State of charge of ESS j in period t
$\overline{SOE}_{t,j}/\underline{SOE}_{t,j}$	The maximum/minimum possible state of charge of ESS j in period t
$T_{t,h}^{in}$	Indoor temperature of house h in period t
$\overline{T}_{t,h}^{in}/\underline{T}_{t,h}^{in}$	The maximum/minimum possible indoor temperature of house h in period t
$\overline{\Delta T}_{t,h}/\underline{\Delta T}_{t,h}$	Up/down deviation of indoor temperatures from desired temperatures of house h
$\alpha_{t,h}$	HVAC mode of house h in period t (0 if heating and 1 if cooling)
$\overline{\alpha}_{t,h}/\underline{\alpha}_{t,h}$	HVAC mode related to the maximum/minimum possible power consumption of HVAC house h in period t
$\beta_{t,j}$	Charging/discharging mode of ESS j in period t (0 if ESS discharges and 1 if ESS charges)
$\overline{\beta}_{t,j}/\underline{\beta}_{t,j}$	Charging/discharging mode related to the maximum/minimum possible power of ESS j in period t (0 if ESS discharges and 1 if ESS charges)

1. INTRODUCTION

1.1. Motivation and aim

The main solution to reduce the pollution emission of the electrical energy systems is using renewable energy sources (RESs). For this purpose, the share of the RESs in global electricity generation is increasing so that it reached 26.2% in 2018, and it is predicted to reach 45% by 2040 [1]. However, the system operators face some major problems regarding the uncertain and intermittent behavior of these resources. The intermittent behavior of the RESs, especially the photovoltaic (PV) systems, increases the ramp-up and ramp-down of the net load of the power system [2]. Since by enhancing the high penetration of the PV system the required ramp of the system increases, it seems that the required ramp of the system cannot be supplied through the limited ramping capability of the conventional generating units. The electrical storage systems (EESs) and flexible loads are the main flexible energy resources that can provide both upward and downward flexibility for the system through the flexible ramping product (FRP) market [2]. Therefore, the problem related to the market participation of the aggregator of these resources is a new challenge, which is addressed in this paper.

1.2. Literature review

There are many studies in which the distributed energy resources (DERs) participate either individually or in the form of aggregators and microgrids in energy markets. In [3], the participation of a load aggregator in the day-ahead (DA) and regulation markets was investigated using a developed detailed optimization model. In [4], the microgrid's participation problem in the DA energy market was formulated to improve the economic and environmental indices. For this purpose, the multi-objective demand side management was employed, and the multi-objective ant lion optimization algorithm and the analytical hierarchy process method were chosen to solve the problem. In [5], the DA energy management problem of a microgrid including the RESs, electric vehicles (EVs), and responsive loads was implemented. The proposed problem was formulated as a mixed-integer linear programming (MILP) model. In [6], the participation process of an ESS aggregator (ESSA) in the energy and reserve markets was formulated using a hierarchical optimization model. In [7], the optimal scheduling of a plug-in electric vehicle

(PEV) aggregator to participate in the DA energy and reserve markets was performed by a novel optimization approach. The rolling horizon approach was proposed in [8] to model the energy management and bidding strategy of a DER aggregator (DERA) in the energy markets. In [9], the decision-making problem of a demand response (DR) aggregator to participate in the energy market was formulated through a bi-level optimization approach in which the upper- and lower-level problems specify the participation of the aggregator in the market and the behavior of the customers, respectively. In [10], the price elasticity as well as the benefit of the customers were taken into account in the decision-making framework of a DR aggregator participating in the DA energy market. Regarding flexible resources, the DER aggregator has a remarkable ability to obtain significant profit in the real-time (RT) energy market. In [11], a bi-level optimization approach was implemented for a DER aggregator's decision-making problem to participate in the RT energy market. In [12], a bi-level optimization approach was used to model the bidding strategy of a prosumer aggregator including the heating, ventilation, and air conditioning (HVAC) loads, residential loads, PVs, and ESSs in the DA energy market. In the proposed model, the aim of the upper- and lower-level problems was to maximize the aggregator profit and the social welfare, respectively.

Recently, few papers have modeled the joint participation of various flexible DERs in both energy and FRP markets. In [13], the operational flexibility required in the power systems under the integration of HVACs was indicated by a multi-stage multi-resolution robust unit commitment. In this study, the non-deterministic variability-based reserves were considered as well. In [14], a gray-box model (i.e., the hybrid model) was presented for the HVACs to provide the ancillary services. This type of HVAC model has some major disadvantages, such as the challenges to develop the model and the accuracy that remarkably depends on the integrity of the data to train the model. In [15], the participation of only the EV aggregators, due to their flexibility, in both the energy and FRP markets was investigated. For this purpose, an AC optimal power flow (ACOPF) was developed to simultaneously minimize the operation costs related to providing energy and FRP capacities. In [16], the decision-making of an ESSA to provide the FRP in the DA energy and reserve markets was formulated using an optimization approach. The main aim was to not only utilize the flexibility of the ESSs but also maximize the profit of the ESSA. In [17], a linear deterministic programming approach was proposed for the problem of profit maximization of an ESSA participating simultaneously in energy and FRP markets. In [18], an optimization framework was extended for ESSs to participate in the RT energy market considering its strategy in the FRP market. A decision-making framework was modeled in [19] with the aim of specifying the simultaneous optimal strategy of combined heat and power (CHP) in the DA energy and FRP markets. In [20], a co-optimization problem was proposed to indicate the bidding strategy of the thermal and wind units taking into account the FRP production of thermal units in the DA energy and FRP markets. In [21], the participation of two types of EVs in the energy and FRP markets was modeled. In this paper, the results of two cases, including 1) only EV and 2) the joint EV and conventional generators, were addressed. In [22], a market-based model considering the competition among the conventional distributed generations (DGs), RESs, and ESSs in the form of an aggregator was indicated. In this work, the impact of ramp-limited DGs in conjunction with the RESs as well as the ESSs on the efficiency of the energy and FRP market was addressed.

Regarding the overall investigation of the presented works, the following gaps are clarified:

- In [3-12], modeling as well as the players participating in the FRP market was ignored. In other words, the ability of the DERs to provide ancillary services was not considered.
- In [17-20], the DERs were individually scheduled to participate in the energy and FRP market. However, according to the high level of distribution as well as the number of DERs and loads, there was a need for preparing a communications infrastructure to tackle the problems of the share of wide information. This structure was remarkably sophisticated and impractical in the real operation of the system.
- In [3-11, 15-21], the capability of flexible loads consisting of HVAC was not modeled to provide FRP services.

Hence, the main purpose of this paper is to fill the aforementioned gaps by presenting a decision-making framework for an aggregator to participate in both the energy and FRP markets. In general, the main contributions of this survey are the following:

- Development of a decision-making framework for an aggregator to schedule the flexible sources to participate simultaneously in both the DA energy and FRP market.

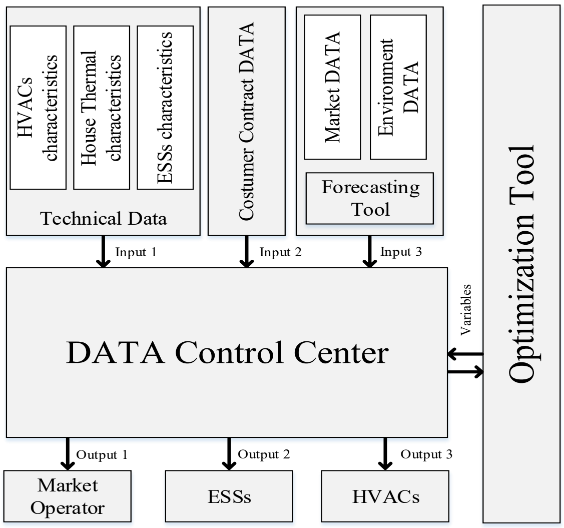

Fig. 1. The process of the optimization method

Table 1. Details of inputs and outputs mentioned in Fig. 1

Input parameters	Input 1	k_1, k_2, k_3, k_4 , $P_h^{\max\_AC}/P_h^{\max\_H}$, $P_j^{\max\_dc}/P_j^{\max\_dch}$, SOE_j^{max}/SOE_j^{min}
	Input 2	$\overline{DB}_h/\underline{DB}_h$, k_{cw}, $T_{t,h}^{des}$
	Input 3	$\lambda_t^{DA}, \lambda_t^{RT}$, π_t^{up}/π_t^{dn} , ρ_t^{up}/ρ_t^{dn} , β, T_t^a
Output decision variables	Output 1	P_t , Rup_t/Rdn_t
	Output 2	$P_{t,j}^{ch}, P_{t,j}^{dch}, Rup_{t,j}^{ESS}, Rdn_{t,j}^{ESS}$
	Output 3	$P_{t,h}^{AC}, P_{t,h}^{H}, Rup_{t,h}^{FL}, Rdn_{t,h}^{FL}$

- Modeling the HVAC, as a flexible load and an FRP provider, in the market. In addition, the customers' welfare is considered in the proposed optimization model appropriate for the real operation.

1.3. Paper organization

The structure of the paper is classified as follows: Section 2 describes the problem. The optimization model is formulated in section 3. Section 4 investigates the numerical results, and the paper is concluded in section 5.

2. PROBLEM DESCRIPTION

2.1. Optimization process

The steps of the aggregator's decision-making framework are clarified in Fig. 1 and Table 1. In the first step, the required data of the aggregator are collected in the data control center. These data include the technical data from the DERs (i.e., the HVACs, house thermal, and ESS characteristics), the customer contracts data, and the forecast data (i.e., market prices as well as environmental characteristics). Then, the collected data are sent to the optimization tool in which the decision-making problem of the aggregator is formulated as a MILP model. The optimization problem is solved in this center using the appropriate tools by which the decision variables of the aggregator are determined and they are sent to the data control center. On the one hand, this center sends the obtained bids to the DA and FRP markets, and on the other, it sends the optimal scheduling set-points to the energy resources.

2.1. HVACs definition

HVACs are flexible loads that control the house temperature based on the customer's desired temperature. House temperature HVAC can minimize its energy cost by changing its load according to hourly energy price and temperature constraints. Moreover, houses' thermal inertia allows HVACs to either increase or decrease their load immediately without exceeding the related temperature constraint. In addition, HVACs have the capability to provide FRP service.

3. MATHEMATICAL FORMULATION

3.1. Objective function

The objective function of the aggregator is formulated as (1) and consists of three terms. The first term is used to model the revenue of trading energy with the DA energy market as described in (2). The revenue of the aggregator from participating in the FRP market is modeled in the second term (3), and the third term is used to model the cost of improving the customer's welfare considering the deviation of indoor temperature from the desired one as shown in (4).

$$\max \ R_{en} + R_{ra} - C_{cw} \tag{1}$$

$$R_{en} = \sum_t \lambda_t^{DA} P_t \tag{2}$$

$$R_{ra} = \sum_t (\pi_t^{up} \beta Rup_t + \pi_t^{dn} \beta Rdn_t + \pi_t^{up} \rho_t^{up} \lambda_t^{RT} Rup_t) \tag{3}$$

$$C_{cw} = \sum_t \sum_h k_{cw} (\overline{\Delta T}_{t,h} + \underline{\Delta T}_{t,h}) \tag{4}$$

This objective function is solved considering the following constraints.

3.2. Energy, ramp-up, and ramp-down balance constraints

The power exchange of the aggregator with the DA energy market is modeled as (5) where this power is equal to the sum of the power exchange of the flexible loads and EESs with the aggregator. Moreover, the sum of the upward and downward ramp provided by the flexible loads and EESs is equal to this capacity provided for the market as modeled in (6) and (7).

$$P_t = \sum_j P_{t,j}^{ESS} + \sum_h P_{t,h}^{FL} \tag{5}$$

$$Rup_t = \sum_j Rup_{t,j}^{ESS} + \sum_h Rup_{t,\mathrm{h}}^{FL}$$
(6)
$$Rdn_t = \sum_j Rdn_{t,j}^{ESS} + \sum_h Rdn_{t,\mathrm{h}}^{FL}$$
(7)

3.3. HVAC constraint

To model the dynamic behavior of the indoor temperature in this paper, Eq. (8) and (9) are used. It should be noted that such modeling of the indoor temperature was previously suggested in [23] and [24]. The indoor temperature of each house is determined based on the indoor temperature of the previous period, ambient temperature, and HVAC's cooling or heating power as modeled in (8). The parameters $k_1 - k_4$ are defined as (9).

$$.T_{t,h}^{in} = k_1 T_{t-1,h}^{in} + k_2 T_{t-1}^{a} - k_3 P_{t,h}^{AC} + k_4 P_{t,h}^{H} \tag{8}$$

$$k_1 = 1 - \frac{\Delta T}{1000.M_h.C_a.R_h^{eq}} \quad , \quad k_2 = \frac{\Delta T}{1000.M_h.C_a.R_h^{eq}}$$
$$k_3 = -\frac{COP_h^{AC}.\Delta T}{0.000277.M_h.C_a.R_h^{eq}} \quad , \quad k_4 = \frac{COP_h^{H}.\Delta T}{0.000277.M_h.C_a} \tag{9}$$

In addition, the indoor temperature should be within the allowable range. $\overline{DB}\,/\,\underline{DB}$ represents the allowed up/down deviation of indoor temperatures from the desired temperature, and $\overline{\Delta T}/\underline{\Delta T}$ represents the actual up/down deviation of indoor temperatures from the desired ones as modeled in (10) and (11). Moreover, in (12) indicates that the indoor temperature at the first and last steps should be equal.

$$T_{t,h}^{in} \le T_{t,h}^{des} + \overline{\Delta T}_{t,h} \quad , \quad T_{t,h}^{in} \le T_{t,h}^{des} + \overline{DB}_t \tag{10}$$

$$T_{t,h}^{des} - \underline{DB}_t \le T_{t,h}^{in} \quad , \quad T_{t,h}^{des} - \underline{\Delta T}_{t,h} \le T_{t,h}^{in} \tag{11}$$

$$T_{1,h}^{in} = T_{\mathrm{T},h}^{in} \tag{12}$$

Depending on the conditions, the HVAC will be in the cooling or heating mode, and one of the P^{AC} and P^{H} will be non-zero as defined in (13) and (14). On the other hand, the flexible load is equal to the total HVAC load of each house as (15).

$$P_{t,h}^{AC} \le \alpha_{t,h} P_h^{\max\_AC} \tag{13}$$

$$P_{t,h}^{H} \le (1-\alpha_{t,h}) P_h^{\max\_\mathrm{H}} \tag{14}$$

$$P_{t,h}^{FL} = P_{t,h}^{AC} + P_{t,h}^{H} \tag{15}$$

The amount of the ramp-up that the HVAC system can provide for the aggregator equals minus the scheduled power of the HVAC and the minimum power that can be consumed by the HVAC system. For this purpose, the minimum power consumption of the HVAC should be modeled, and the temperature constraints of the HVAC must be considered. Therefore, the previous constraints ((8)-(14)) are rewritten considering the "underline" symbol on the variables as modeled in (16)-(20).

$$\underline{T}_{t,h}^{in} = k_1 \underline{T}_{t-1,h}^{in} + k_2 T_{t-1}^{a} - k_3 \underline{P}_{t,h}^{AC} + k_4 \underline{P}_{t,h}^{H} \tag{16}$$

$$T_{t,h}^{des} - \underline{DB}_t \le \underline{T}_{t,h}^{in} \le T_{t,h}^{des} + \overline{DB}_t \tag{17}$$

$$\underline{P}_{t,h}^{FL} = \underline{P}_{t,h}^{AC} + \underline{P}_{t,h}^{H} \tag{18}$$

$$\underline{P}_{t,h}^{AC} \le \underline{\alpha_{t,h}} P_h^{\max\_AC} \tag{19}$$

$$\underline{P}_{t,h}^{H} \le \left(1-\underline{\alpha_{t,h}}\right) P_h^{\max\_H} \tag{20}$$

The amount of the ramp-down that the HVAC system can provide for the aggregator equals minus the scheduled power of the HVAC and the maximum power that can be consumed by the HVAC system. For this purpose, the maximum power consumption of the HVAC should be modeled, and the temperature constraints of the HVAC must be considered. Therefore, the previous constraints ((8)-(14)) are rewritten considering the "overline" symbol on the variables as modeled in (21)-(25).

$$\overline{T}_{t,h}^{in} = k_1 \overline{T}_{t-1,h}^{in} + k_2 T_{t-1}^{a} - k_3 \overline{P}_{t,h}^{AC} + k_4 \overline{P}_{t,h}^{H} \tag{21}$$

$$T_{t,h}^{des} - \underline{DB}_t \le \overline{T}_{t,h}^{in} \le T_{t,h}^{des} + \overline{DB}_t$$
(22)

$$\overline{P}_{t,h}^{FL} = \overline{P}_{t,h}^{AC} + \overline{P}_{t,h}^{H} \tag{23}$$

$$\overline{P}_{t,h}^{AC} \le \overline{\alpha_{t,h}} P_h^{\max\_AC} \tag{24}$$

$$\overline{P}_{t,h}^{H} \le \left(1-\overline{\alpha_{t,h}}\right) P_h^{\max\_H} \tag{25}$$

where variables corresponding to the maximum load of the HVAC are represented by the overlined variables formulated as (16)-(20). Similarly, variables corresponding to the minimum load of the HVAC are represented by the underlined variables in (21)-(25). In addition, in (26) the up/down FRP provided by the HVAC is determined according to the difference between the minimum/maximum load of HVAC and its DA load [23, 24].

$$Rup_{t,h}^{FL} = P_{t,h}^{FL} - \underline{P}_{t,h}^{FL} \quad , \quad Rdn_{t,h}^{FL} = \overline{P}_{t,h}^{FL} - P_{t,h}^{FL} \tag{26}$$

3.4. ESS constraints

Depending on the charging or discharging mode, the ESS power exchange and the state of charge (SOC) are determined in (26)-(31) as follows [16]. Equation (27) specifies the output power of the ESSs. The dynamic behavior of the energy stored in the ESS, as well as the upper and lower bounds of this energy, is formulated in (28) and (29). Furthermore, the equality of the energy at the first and last time steps is shown in (30). In addition, Equations (31) and (32) force the ESS not to charge and discharge simultaneously.

$$P_{t,j}^{ESS} = P_{t,j}^{ch} - P_{t,j}^{dch} \quad (27)$$

$$SOC_{t,j} = SOC_{t-1,j} + \eta_j^{ch} P_{t,j}^{ch} - \frac{P_{t,j}^{dch}}{\eta_j^{dch}} \quad (28)$$

$$SOC_j^{\min} \le SOC_{t,j} \le SOC_j^{\max} \quad (29)$$

$$SOC_{0,j} = SOC_{T,j} \quad (30)$$

$$P_{t,j}^{ch} \le \beta_{t,j} P_j^{\max\_ch} \quad (31)$$

$$P_{t,j}^{dch} \le (1-\beta_{t,j}) P_j^{\max\_dch} \quad (32)$$

Regarding the previous constraints (27)-(32), the maximum/minimum possible power exchanges of ESS are determined as follows:

$$\overline{P}_{t,j}^{ESS} = \overline{P}_{t,j}^{ch} - \overline{P}_{t,j}^{dch} \quad (33)$$

$$\overline{P}_{t,j}^{ch} \le \overline{\beta}_{t,j} P_j^{\max\_ch} \quad (34)$$

$$\overline{P}_{t,j}^{dch} \le (1-\overline{\beta}_{t,j}) P_j^{\max\_dch} \quad (35)$$

$$\overline{SOC}_{t,j} = SOC_{t-1,j} + \eta_j^{ch} \overline{P}_{t,j}^{ch} - \frac{\overline{P}_{t,j}^{dch}}{\eta_j^{dch}} \quad (36)$$

$$SOC_j^{\min} \le \overline{SOC}_{t,j} \le SOC_j^{\max} \quad (37)$$

$$\underline{P}_{t,j}^{ESS} = \underline{P}_{t,j}^{ch} - \underline{P}_{t,j}^{dch} \quad (38)$$

$$\underline{P}_{t,j}^{ch} \le \underline{\beta}_{t,j} P_j^{\max\_ch} \quad (39)$$

$$\underline{P}_{t,j}^{dch} \le (1-\underline{\beta}_{t,j}) P_j^{\max\_dch} \quad (40)$$

$$\underline{SOC}_{t,j} = SOC_{t-1,j} + \eta_j^{ch} \underline{P}_{t,j}^{ch} - \frac{\underline{P}_{t,j}^{dch}}{\eta_j^{dch}} \quad (41)$$

$$SOC_j^{\min} \le \underline{SOC}_{t,j} \le SOC_j^{\max} \quad (42)$$

Based on the difference between the minimum/maximum ESS power and the DA power, the up/down FRP of ESS is determined in (43).

$$Rup_{t,j}^{ESS} = P_{t,j}^{ESS} - \underline{P}_{t,j}^{ESS} \quad , \quad Rdn_{t,j}^{ESS} = \overline{P}_{t,j}^{ESS} - P_{t,j}^{ESS} \quad (43)$$

4. NUMERICAL RESULTS

4.1. Input data

In this model, there are two types of ESSs and residential HVACs managed by the aggregator. The ESSs' characteristics are listed in Table 2. The modified coefficients of the HVAC models are also presented in Table 3. Furthermore, Fig. 2 shows the hourly estimated DA and RT energy market prices. Of note that, the demand price of FRP is assumed to be 8 \$/MWh, and the acceptance and deployed probabilities of the up/down FRP are $\boldsymbol{\pi_t^{up} = \pi_t^{dn} = 0.4}$ and $\boldsymbol{\rho_t^{up} = \rho_t^{dn} = 0.3}$, respectively. Moreover, the ambient temperature is indicated in Fig. 3, and the desired temperature of each house is equal to $\mathbf{22}$°C [16, 24].

Table 2. The ESSs' characteristics

ESS	Capacity (kWh)	η^{ch}	η^{dch}	SOC^{min} (kWh)
Type 1	50	0.95	0.95	5
Type 2	100	0.95	0.95	10
ESS	SOC^{max} (kWh)	$P^{\max\_ch}$ (kW)	$P^{\max\_dch}$ (kW)	
Type 1	45	5	5	
Type 2	90	10	10	

Table 3. The HVACs' characteristics

HVAC's parameters	Value	
	Type 1	Type 2
$P^{\max\_AC}$ (kW)	10	10
$P^{\max\_H}$ (kW)	20	20
k_1	0.212	0.212
k_2	0.788	0.788
k_3	7.1	7.1
k_4	5	5
ΔT (h)	1	1
M_h (kg)	400	400
C_a (kj/kg°C)	1.01	1.01
R_h^{eq} (h°C/j)	3.14*10^{-6}	3.14*10^{-6}
COP_h^{AC}	0.8	0.8
COP_h^{H}	0.55	0.55

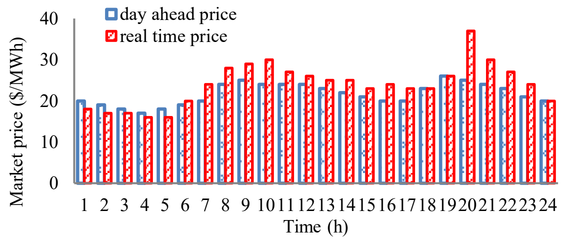

Fig. 2. The DA and RT market prices

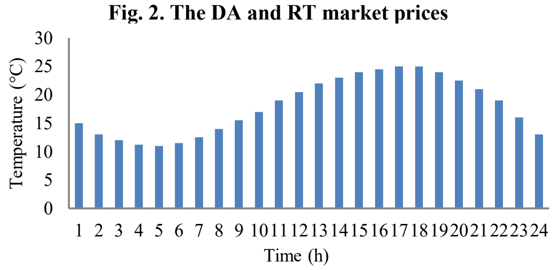

Fig. 3. The ambient temperature

4.2. Results

To evaluate the effectiveness of the proposed method, four different cases are considered as follows:

Case 1: Aggregator's bids in only the energy market

In this case, the ESS charges during the low-price hours, and by contrast, it discharges over the hours when the energy price is high. It is notable that, regarding Fig. 4 and 5, the HVAC attempts to keep the temperature of the house at the allowable temperature with the least amount of energy. Thus, more energy is consumed during the hours with a significant difference between the ambient temperature and the desired indoor temperature.

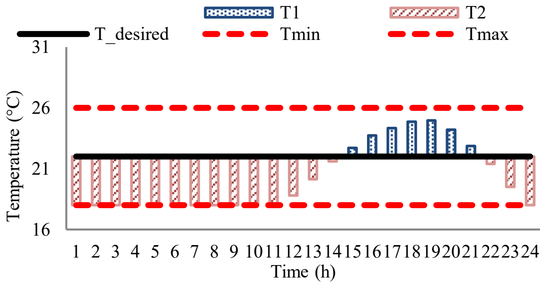

Fig. 4. The indoor temperature deviation in Case 1

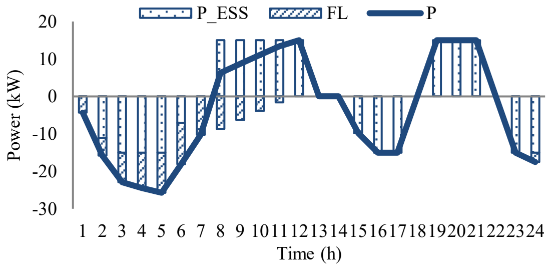

Fig. 5. The energy market bids in Case 1

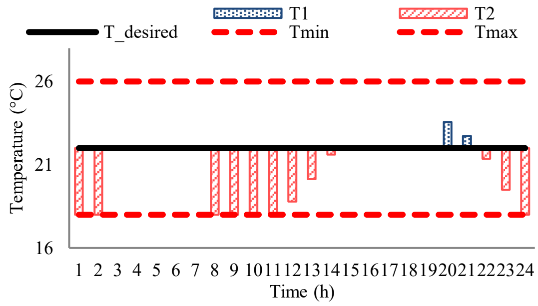

Fig. 6. The indoor temperature deviation in Case 2

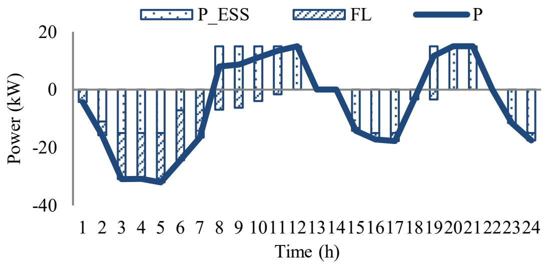

Fig. 7. The energy market bids in Case 2

Case 2: Aggregator's bids in only the energy market considering the customers' welfare

In this case, in addition to participating in the energy market, the aggregator aims to keep the indoor temperature considerably close to the desired temperature, especially during hours with low energy prices (Fig. 6). Thus, keeping the indoor temperature close to the desired temperature led to more energy consumption by HVACs (see Fig. 7). Compared to the previous case, the indoor temperature is 1.3℃ closer to the desired temperature on average, but the power consumption of HVAC has increased by 54.3%.

Case 3: Aggregator's bids in joint energy and FRP markets

In this case, only the participation of the aggregator in the energy market is analyzed. As shown in Fig. 8 and 9, the maximum and minimum powers consumed by the HVAC depend on the constraints such as maximum and minimum allowable indoor temperature and the maximum power of the HVAC. In addition, the maximum power that the ESS can generate or consume depends on the ESS constraints such as maximum charging/discharging and maximum/minimum SOC of the ESS. The share of the ESSs as well as the HVAC system to provide the FRP capacity in the FRP market is depicted in Fig. 10.

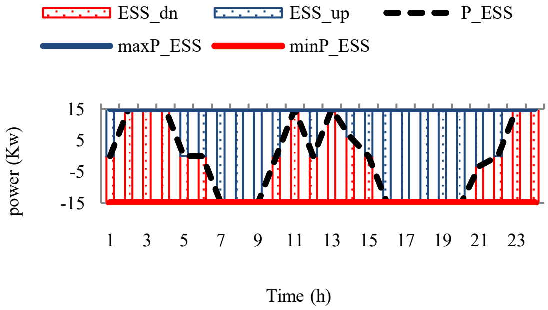

Fig. 8. The DA bids of ESS in Case 3

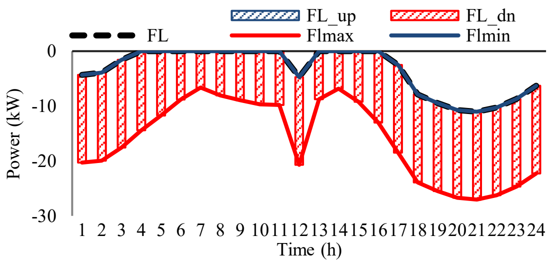

Fig. 9. The DA bids of HVAC in Case 3

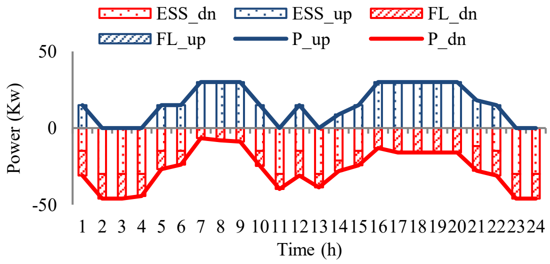

Fig. 10. The FRP provided by the aggregator in Case 3

Case 4: Aggregator's bids in joint energy and FRP markets considering the customers' welfare

In this case, the aggregator participates in the joint energy and FRP markets taking the customer's welfare into account. The share of energy as well as the ramp capacities provided by the ESSs and the HVACs are depicted in Fig. 11-13. As observed in these figures, the total revenue obtained from the energy and the FRP markets decreases by about 48% compared to Case 3. However, regarding the customer's welfare engaged in this case, the cost of temperature deviation exhibits a reduction of 130%. Hence, the results of this case are more accurate than those obtained from the former case (i.e., Case 3) in the real operation of the system.

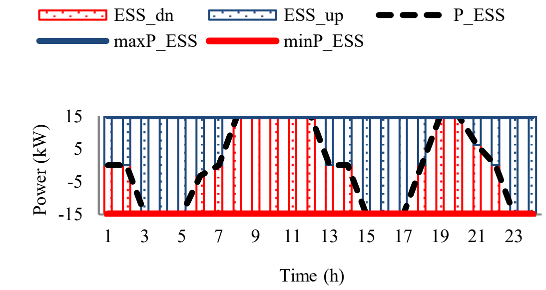

Fig. 11. The DA bids of ESS in Case 4

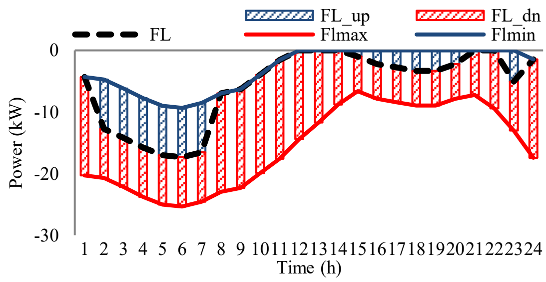

Fig. 12. The DA bids of HVAC in Case 4

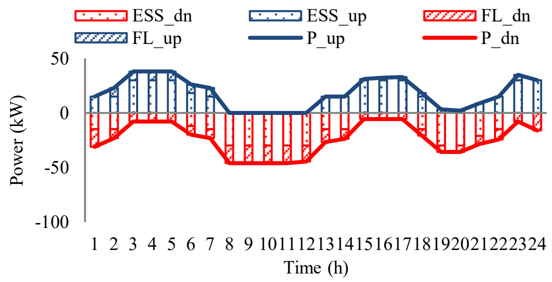

Fig. 13. The FRP provided by the aggregator in Case 4

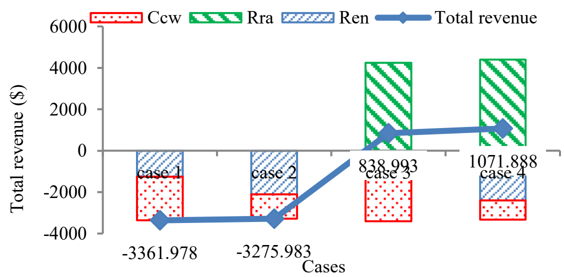

Fig. 14. The comparison of the cases

4.3. Discussion

In this section, all the terms of the total revenue regarding cases 1-4 analyzed in the previous section are reported in Fig. 14 and Table 4. Based on the engagement of the customer's welfare factor as a penalty term, the indoor temperature of the houses gets closer to the desired one. Therefore, the penalty of the temperature deviation diminishes, and the energy consumption of the HVACs increases. As a result, the revenues obtained from the energy market in Cases 2 and 4 decrease compared to Cases 1 and 3, respectively. On the other hand, the aggregator, in Cases 3 and 4, has the opportunity to gain more revenue by participating in the joint energy and FRP markets. As can be seen in Fig. 14 and Table 4, the aggregator obtains the revenue of 4237.44$ and 4395.55$ in Cases 3 and 4, respectively, through optimal decision-making to provide ramping capacities in the FTP market.

4.4. Sensetivity analysis

One of the most important factors related to the participation of the aggregator in the FRP market is the probability of deploying flexibility bids. As concluded in Fig. 15, as the probability of FRP deployment increases, the flexibility market's revenue increases as well. On other hand, this raises the cost of the energy market, but the total aggregator's revenue will increase as well. According to Fig. 16, improving the customers' welfare by setting the indoor temperature closer to the desired temperature causes the HVAC to consume more energy. This is accomplished by increasing the weight factor k, and after a while, it is not possible to reduce the difference between the desired temperature and the indoor temperature.

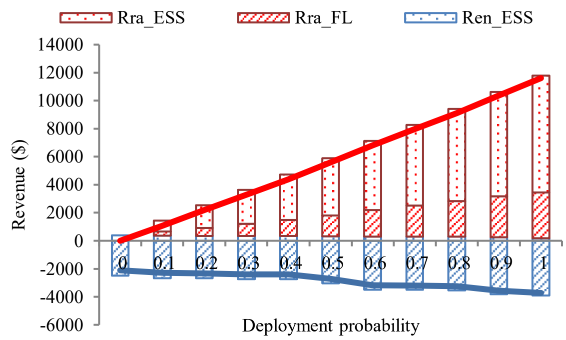

Fig. 15. The impact of the FRP deployment probability on the total revenue

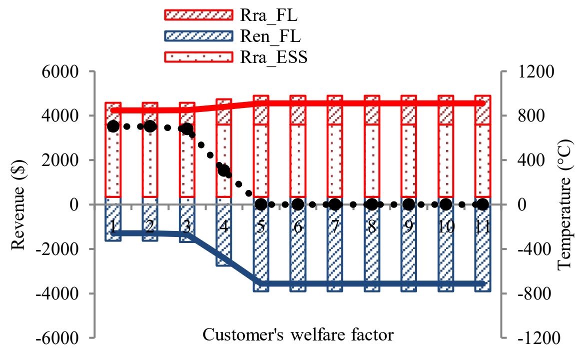

Fig. 16. The impact of the customers' welfare factor on the total revenue

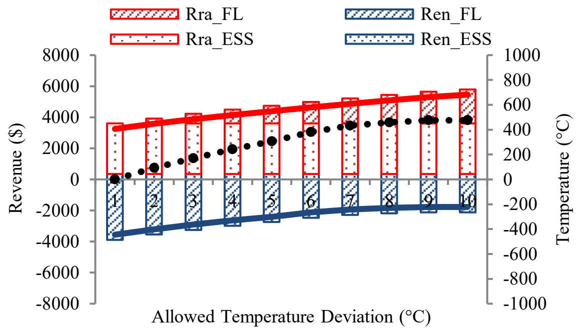

Fig. 17. The impact of the temperature deviation on the total revenue

Table 4. The components of the revenue as well as the cost in the four cases

Cost/revenue terms	Cases			
	Case 1	Case 2	Case 3	Case 4
Total revenue ($)	-3361.98	-3275.98	838.993	1071.888
Revenue of the energy market ($)	-1255.09	-2108.8	-1291.57	-2406.62
Revenue of the FRP market ($)	0	0	4237.443	4395.555
Revenue of the energy market by the flexible loads ($)	-1634.17	-2487.88	-1634.17	-2749.22
Revenue of the energy market by the ESS ($)	379.072	379.072	342.6	342.6
Revenue of the FRP market by the flexible loads ($)	0	0	985.005	1143.116
Revenue of the FRP market by the ESS ($)	0	0	3252.439	3252.439
Cost of deviation of temperature ($)	-2106.89	-1167.18	-2106.89	-917.052

Fig. 17 describes that the aggregator has more choices in the HVAC operation based on the expansion of the allowable temperature range. As it expands, the energy and FRP profits will increase. After a while, range expansion does not impact DA offers.

5. CONCLUSIONS

In this paper, a decision-making framework is proposed for a DERA that participates in the energy and FRP markets. Hence, the co-optimization method is imposed to model such a framework and the problem is solved using the MILP approach. Meanwhile, the ESSs, as well as HVAC increase the ability of DERA to obtain more profit from the markets. Hence, the major conclusions to be drawn from the results and sensitivity analysis are as follows:

- The DERA's total revenue in Case 1, in which the customer's welfare is overlooked, is equal to -1255$. Therefore, when the customer's welfare is calculated out of the optimization process, as a penalty term, the final total revenue changes to -3361.95$.
- The optimization problem is amended in Case 2 by adding the penalty term, i.e., customer's welfare, to the objective function. As a result, the DERA's decisions are accurately changed based on this additional term. The final total revenue is affordably modified to -3275.98$.
- Taking the customer's welfare into account results in a higher level of HVAC power consumption in Case 2 (by 52.2%) and a lower devotion between the indoor temperature and the desired temperature in comparison with Case 1.
- The joint participation in the energy and FRP markets in Cases 3 (without customer's welfare) and 4 (with customer's welfare), by implementing the entire potential of the ESSs and the HVAC considerably increases the DERA's total revenues from -3361.98$ and -3275.98$, in Cases 1 and 2, to 838.99$ and 1071.89$, in Cases 3 and 4, respectively.
- When the probability of the FRP deployment rises, the DERA has an opportunity to sell the deployed FRP capacity in the real operation in the market. Therefore, the change of deployment probability from 0 to 1 increases the revenue obtained from the FRP market from 0$ to 11610.49$.
- The HVAC consumes more energy by raising the customer's welfare from 0 to 10, and therefore, the revenue of energy decreases from -1291.56$ to -3560.19$. However, the DERA can enhance the revenue by participating in the FRP market which not only increases the revenue of providing ramping products from 4237.44$ to 4556.75$ but also decreases the deviation from the desired temperature to zero.
- The summation of energy and FRP revenues is remarkably affected (the increase from -307.76$ to 3827.14$) due to the change of the allowed temperature deviation from 1°C to 10°C.

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