Optimal Behavior of Smart Households Facing with both Price-based and Incentive-based Demand Response Programs

M. Shafie-khah[1], S. Javadi[1], P. Siano[2], J.P.S. Catalão[1,3,4]
[1] C-MAST, University of Beira Interior, Covilhã, Portugal, [2] University of Salerno, Fisciano (SA), 84084 Salerno, Italy,
[3] INESC TEC and FEUP, Porto 4200-465, Portugal, [4] INESC-ID, IST, Univ. Lisbon, Lisbon 1049-001, Portugal
miadreza@ubi.pt; ss.ja85@yahoo.com; psiano@unisa.it; catalao@fe.up.pt

***Abstract*—Because of various developments in communications and technologies, each residential consumer has been enabled to contribute in Demand Response Programs (DRPs), manage its electrical usage and reduce its cost by using a Household Energy Management (HEM) system. An operational HEM model is investigated to find the minimum consumer's cost in every DRP and to guarantee the end-user's satisfaction, as well as to ensure the practical constraints of every battery and residential appliance. The numerical studies show that the presented method considerably affects the operational patterns of the HEM system in each DRP. According to the obtained results, by employing the presented method the consumer's cost is decreased up to 40%.**

***Index Terms*—Battery, demand response, household energy management, incentive, tariff.**

NOMENCLATURE

A. Superscripts

Acc	Acceptable time or operation mode by the end-user.
App	Electrical residential appliance.
B	Battery.
B2G	Battery to the grid.
B2H	Battery to home.
ch	Charging mode.
Cntrl	Control/manageable appliances or a part of demand.
Crit	Critical appliances or a part of demand.
Degr	Battery degradation because of V2G mode.
dis	Discharging mode.
ini	Initial value of price or demand.
G	Grid.
G2H	Grid to home.
H	Home.
H2G	Home to the grid.
H2B	Home to the battery.
Nom	Nominated amount of residential appliance's electrical usage.

B. Indexes

i	Control/manageable residential appliances.
t	Times.

C. Operator

Δ	Change in variable amounts.

D. Parameters and Variables

B	Consumer's benefit.
Cap	Battery capacity.
$Cost_B$	Capital expenditure of battery.
C_d	Cost of battery degradation.
d	Electrical load.
Inc	Incentive rate arisen from decreasing the load.
L_{ET}	Battery's lifetime.
P	Active power.
Pen	Penalty rate arisen from not decreasing the load.
r	Charge/discharge rates of battery.
Rev	Consumer's revenue.
SOC	State of the Charge of battery.
s	On/off state indicator of control/manageable residential appliances.
v	Inelasticity parameter of residential appliances.
V	Consumer's dissatisfaction compared to the fixed-rate load.
WP	Working period of controllable residential appliances.
η	Efficiency.
π	Scenarios' probability.
λ	Electricity tariff.
ς	Incentive.
ξ	Penalty.
χ,γ	Binary variables for bi-directional power.

I. INTRODUCTION

Smart grid subject has achieved lots of attention with some great investments around the world regarding the conception of operative deregulation of developed electric industries. Smart grid concept can improve the power system efficiency from generation side to the end-user side, considering the contribution of the consumer [1], [2].

Smart households, which detect the usage and operate to lessen the electricity cost, have prepared the bases to empower the activity of end-user side by the association of increasing importance of smart grid concept [3]. The essential fundamentals of the smart grids in the future, to empower the contribution of end-users, are Demand Response Programs (DRPs) [4].

In order to decrease the pressure on utility-handled equipment's like lines and transformers, DRPs mostly focus on changing the customers' consumption from peak to off-peak periods and can prepare a beneficial source for efficient operations of smart grids [5].

In order to decrease the electricity consumption in a way that the habitants' comfort levels are met, the household electricity consumption needs to pursue the DRPs through shifting and curtailing the electricity load [6].

The influence of DR on the demand pattern has been studied in an economic model of tariff-responsive demands in [7]. Also, there are lots of investigations in the concept of DR strategy for smart homes. For example, an optimization approach to the efficient home energy operation has been utilized in [3] and [8] taking a tariff-based DR into account.

A Household Energy Management (HEM) has been performed in [9] and [10] using DR strategies in order to constrain the electricity peak of the home. The influences of electric vehicles and DR on distribution transformers have been presented in [4] and in order to reduce the disadvantages of PEVs on load peaks, a load-shaping tool has been marked.

In addition, a DR framework has been investigated on the evaluation of the end-user's responses to DRPs [11]. Despite of lots of research in the literature, the influence of both incentive- and price-based DRPs and end-users comfort on the performance of HEMs has been hardly reported.

Finding the optimum performance for HEMs by studying the customers' satisfaction in operating various residential appliances in both incentive- and price-based DR programs is the main goal of this paper. The assessment of the behavior of an HEM under different DR strategies is the main contribution of this paper.

The remainder of the paper is structured as follows. In section II, the model of DRPs is introduced. Section III is devoted to the formulation of the presented framework of the household energy management system. Section IV is dedicated to the numerical results and section V concludes the paper.

II. MODELING THE DEMAND RESPONSE

Making consumer more sensitive about the electricity price variations at various hours is the DRPs aim. DRPs inspire the electricity customer to shift their usage of electricity according to the variations of price through the time, to bid the incentive, or to charge the penalty provided to make lower consumption through peak hours or when the power system reliability is at risk. DRPs are classified into two main sets, which are price-based and incentive-based programs. Incentive-based DRPs include Emergency DRP (EDRP) and Interruptible/Curtailable (I/C) services. While, price-based DRPs consist of Time of Use (TOU), Real-Time Pricing (RTP) and Critical Peak Pricing (CPP). More details have been explained in [12].

The end-user's electricity consumption at time t is assumed to change from initial demand, to d_t, because of price variations or incentive payments or penalty considerations. The impact of DR strategies on an end-user's load is formulated as below [13]:

$$\Delta d_t = d_t^{ini} - d_t \tag{1}$$

The amount of incentive and penalty can be formulated as (2) and (3), respectively.

$$\varsigma_t = Inc_t \, \Delta d_t \tag{2}$$

$$\xi_t = Pen_t \, \Delta d_t \tag{3}$$

The benefit of the end-user during period T, is presented is (4) [13]:

$$B_{tot} = \sum_{t=1}^{T} \left(Rev_t - d_t \, \lambda_t + Inc_t \, \Delta d_t - Pen_t \, \Delta d_t \right) \tag{4}$$

where Rev_t is an end-user's revenue which is a function of demand, d_t.

Eq. (4) shows a basic formula for calculation of decision variables of the end-user's benefit for the price- and incentive-based DRPs including single- and multi-period responses. The benefit, B_{tot}, defines the variable of an end-user to make a decision to how react to price changes, incentives and penalties. In the rest of the paper, the basic formula will be specifically employed on an end-user.

III. MODELING THE RESPONSIVE SMART HOUSEHOLD

The schematic of a smart home is shown in Fig. 1. According to Fig. 1, the HEM operates the smart home according to the signals from a load server, DR strategies, charging/discharging of battery, critical and control/manageable appliances.

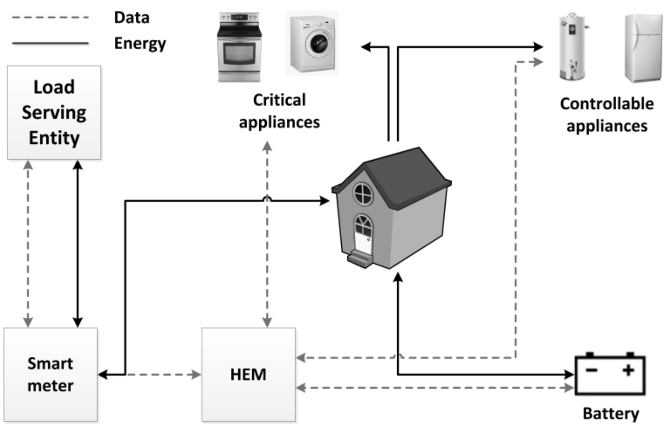


Fig. 1. Schematic of a smart home.

Each DR provider will try to modify the load pattern of its end-users. So, it will motivate each smart home to fix the consumption profile. In the flat tariffs, the consumer has the most convenient personal preference time to use its appliances. For example, through the warmest hours of a day, a large number of end-users operate the air conditioning systems that can cause the peak in demand. In the presented method, financial incentives/penalties of the DR providers inspire the end-users to modify the load pattern. The goal of consumers is to maximize the net payoff [14].

Therefore, in the presented approach, the goal is to find the maximum of the incomes of injecting energy to the load serving entity and incentive of DR strategies minus the cost of receiving energy from the load serving entity, cost of penalty of DRPs, battery's degradation and dissatisfaction costs, as formulated in (5) [15]:

$$\underset{P_t^{H2G}, P_t^{G2H}, Cost_t^{Degr}, V_t}{\text{Maximize}} \quad \{profit^{Household}\} = \sum_t \{P_t^{H2G}\ (\lambda_t^{ini} - \lambda_t) - P_t^{G2H}\ (\lambda_t^{ini} - \lambda_t) - Cost_t^{Degr} + Inc_t\,\Delta P_t^{G2H} - Pen_t\,\Delta P_t^{G2H} - V_t\} \tag{5}$$

The first two terms of equation (5) show the selling income and buying cost earned from transferring the electricity between the home and the load serving entity, respectively. The next term presents the end-user's cost arisen from battery's degradations because of being discharged as presented in (6) [15].

$$Cost_t^{Degr} = \left(P_t^{B2H} + P_t^{B2G}\right) C_d \tag{6}$$

where $Cost_t^{Degr}$ is the end-user's degradation cost and C_d is the battery cost that is recognized as wear for B2G or B2H due to extra cycling of the battery and it is calculated by (7):

$$C_d = \frac{Cost_B}{L_{ET}} \tag{7}$$

It is worthy to note that the degradation cost of battery maintains its lifetime and decreases the priority of discharging the battery compared to other electrical appliances. It means that, HEM modifies the operation of control/manageable appliances before discharging the battery.

The fourth and fifth terms of equation (5) denote the incentive income and penalty cost of participating in the DR strategies. ΔP_t^{G2H} is determined as the initial energy that the home receives from the grid (i.e. in a flat tariff) minus the received energy in an incentive-based DR strategy. The last term, V_t, expresses a function that attains the dissatisfaction arisen from the deviation from the initial consumption given by (8) [15].

$$V_t = v^{App}\left(P_t^{Cntrl} - P_t^{ini,Cntrl}\right) + v^B\left[\left(P_t^{G2B} - P_t^{ini,G2B}\right) + \left(P_t^{ini,B2G} - P_t^{B2G}\right)\right] \tag{8}$$

where P_t^{Cntrl} shows the manageable load and $v \geq 0$ denotes an inelasticity parameter of load [14]. V_t is considered a convex function, because by getting distance from the initial manageable load, the differential dissatisfaction of an end-user increases [14].

$P_t^{ini,Cntrl}$ is the initial consumption profile of manageable part of load that demonstrates the ideal consumption profile disregarding DR strategies. Both kinds of price- and incentive-based programs may encourage the consumers to modify the demand because of the financial aims.

The objective function is minimized by considering the following constraints:

$$P_t^{G2H} + \chi_t^B\ \left(P_t^{B2H} + P_t^{B2G}\right) = P_t^{Cntrl} + P_t^{Crit} + \gamma_t^B\ P_t^{G2B} \tag{9}$$

where P_t^{Crit} is the critical part of the end-user load and it is considered constant, therefore it is not dependent on the DR strategies.

Eq. (9) indicates that the load including the residential one (P_t^{Cntrl} and P_t^{Crit}) and the charging requirements of the battery (P_t^{G2B}), would be either supplied by the bought energy from the load serving entity (P_t^{G2H}) or by the discharging of the battery. χ_t^B and γ_t^B denote two binary variables that do not allow the battery be charged and discharged concurrently as (10).

$$\chi_t^B + \gamma_t^B = 1 \tag{10}$$

The consumption powers of control/manageable appliances are assumed to be equal to their nominated amounts and HEM controls these loads by setting the on/off states, as shown in (11) [15].

$$P_{i,t}^{App} = s_{i,t}^{App}\ P_i^{Nom} \tag{11}$$

The HEM system should consider the working periods of each appliance. Because most of the appliances should not be switched off through the operation such as washing machine. Therefore, equations (12) to (14) ensure that each control/manageable appliance would be continuously used in its working periods.

$$\alpha_{i,t} + \sum_{j=1}^{WP_i-1} \{\beta_{i,t+j}\} \leq 1 \tag{12}$$

$$\alpha_{i,t} - \beta_{i,t} = s_{i,t}^{App} - s_{i,t-1}^{App} \tag{13}$$

$$\alpha_{i,t} + \beta_{i,t} \leq 1 \tag{14}$$

where $\alpha_{i,t}$ and $\beta_{i,t}$ are auxiliary binary variables.

Eq. (15) introduces changes in SOC of battery [15]. Eq. (16) is utilized to prevent being overcharged and to take into account the depth of discharge of battery. The restraints of maximum charging/discharging rates are shown in (17)-(20) [15].

$$SOC_t = SOC_{t-1} \\ \gamma_t^B \, \eta^{ch} \left(\frac{P_t^{B,ch}}{Cap^B} \right) - \chi_t^B \left(\frac{P_t^{B2H} + P_t^{B2G}}{\eta^{dis} \, Cap^B} \right) \tag{15}$$

$$SOC^{min} \leq SOC_t \leq SOC^{max} \tag{16}$$

$$r_t^{ch} = \frac{SOC_t - SOC_{t-1}}{\eta^{ch}} \tag{17}$$

$$r_t^{dis} = (SOC_{t-1} - SOC_t)\, \eta^{dis} \tag{18}$$

$$0 \leq r_t^{ch} \leq r^{ch,max} \tag{19}$$

$$0 \leq r_t^{dis} \leq r^{dis,max} \tag{20}$$

IV. Numerical Results

As it is shown in Tables I and II different price-based and incentive-based DR strategies are considered to investigate the operational behavior of the household.

As it is shown in Table I, in the base case a flat tariff is taken into account to be equal to the mean of tariffs that shows the performance of the HEM regarding taking part in DR strategies. A kind of TOU is investigated where the valley tariff is equal to fifty percent of the off-peak one, and the peak and critical peak tariffs are thirty and fifty percent more than off-peak one, respectively.

The tariff in off-peak hours is assumed to be equal to the flat rate tariff. In CPP program, a very high tariff, 0.15 €/kWh, is considered for the critical peak hours. In Table II, details of EDRP and CPP are given.

In EDRP, a ten percent of the flat tariff, i.e 0.0465 €/kWh, is assumed for the load curtailment. According to this assumption, if an end-user reduces the load in the critical peak hours, DR provider will pay him/her the incentive. To this end, the DR provider may send a DR signal to each end-user to decrease its consumption in an hour.

TABLE I
DETAILS OF ELECTRICITY TARIFFS (€/KWH)

Case	Low-load	Off-peak	Peak	Critical peak
Base case (flat rate tariff)	0.0465	0.0465	0.0465	0.0465
Time of Use	0.0233	0.0465	0.0625	0.0720
Critical Peak Pricing	0.0465	0.0465	0.0465	0. 15

TABLE II
DETAILS OF INCENTIVE-BASED DRPS

Case	Peak	Critical peak
Emergency DR Program	-	0.0465 €/kWh for reduction
Interruptible/Curtailable Service	5 % curtailment for an hour	10 % curtailment for an hour

TABLE III
DETAILS OF HOUSEHOLD BATTERIES

Parameter	value
Maximum charge rate in pu/h	0.2
Maximum discharge rate in pu/h	0.2
Charging efficiency in percent	90
Discharging efficiency in percent	82
Minimum acceptable SOC in percent	30
Maximum acceptable SOC in percent	90
Initial SOC of the battery in percent	50
Capital cost of battery in €	900
Battery lifetime in kWh	43,840,000

TABLE IV
APPLIANCES' PARAMETERS

Appliance	Working period (h)	watt	Initial time	Acceptable time	ν^{App} (€/kWh)
Dishwasher	1	1500	22	8-23	1
Lamp	1	5×80	18-23	18-23	1
Space heating	0.33	1500	-	-	-
Washing machine	2	500	20	18-23	1
Water heating	1	4500	7 & 22	5-7 & 18-22	5

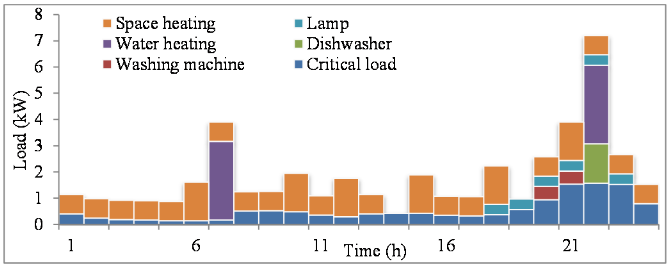


Fig. 2. Initial household demand (disregarding DR programs).

It is assumed that the DR provider asks for reducing the consumption in critical peak period twice of the peak one. A 3 kWh battery is considered. More details are shown in Table III [15].

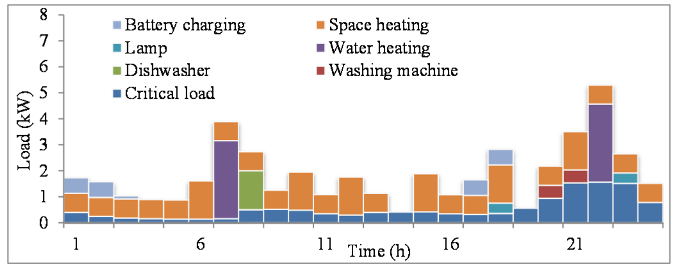
According to Table IV, the end-user would tend to use its water heating at 7 AM and 10 PM. This schedule is changeable according to the acceptable period by the end-user, i.e, 5-7 AM and 7-10 PM, assuming the dissatisfaction rate is equal to 5 €/kWh.

It is worthy to note that, the dissatisfaction rate has not been used for the space heating, since its temperature set point is assumed $25 \pm 1°C$ which guarantees the end-user's satisfaction. As presented in Table IV, besides the critical lamps, 5 extra lamps as control/manageable loads are considered for the end-users to gain the highest satisfaction level.

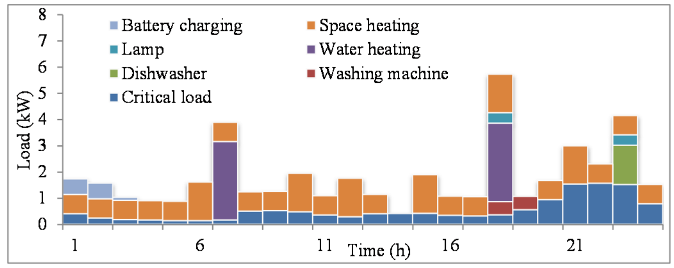
The critical load is obtained from a typical one hundred meter-square apartment in Portugal in January as shown in Fig. 2. The optimization problem is modeled as a mixed integer linear programming and is solved by CPLEX12.

Fig. 3 presents the hourly load of the residential appliances by employing the presented HEM model. Based on Fig. 3a, employing TOU decreases the peak-to-valley factor and makes the load profile smoother. Hence, the HEM has shifted the dishwashing time from the critical peak hours to 8 AM. Also, the noncritical lamps are turned off during critical peak.

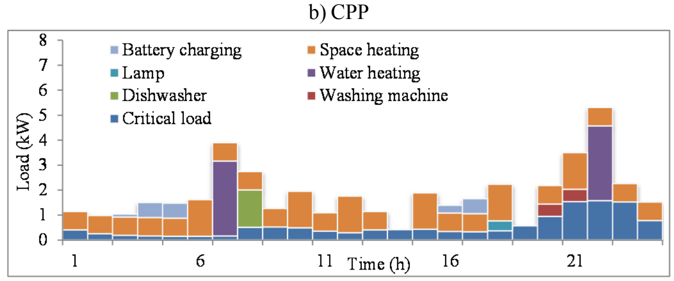
But, the HEM has not changed the schedule of washing machine. Due to restrictions of the acceptable time, HEM can operate the washing machine between 6 PM and 11 PM. Since the operation of the washing machine takes two hours, by shifting the operation time out of the critical peak hours, only a part of its operation time (i.e., an hour) goes to the off-peak hours and the other part (i.e., an hour) stays in the critical peak. On this basis, the HEM has not chosen the shifting because of the associated dissatisfaction cost. Similarly, the HEM does not change the operation time of water heating because of the considerable dissatisfaction cost. Furthermore, the battery has been charged in both the low-load and off-peak hours.



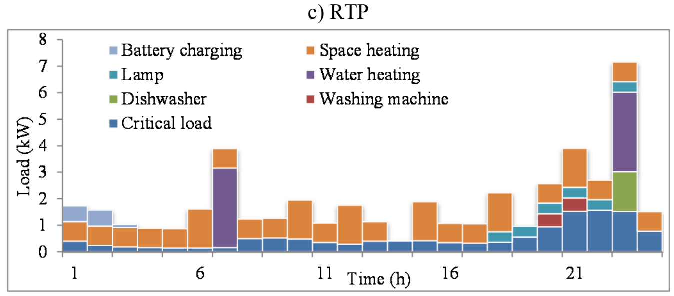
a) TOU



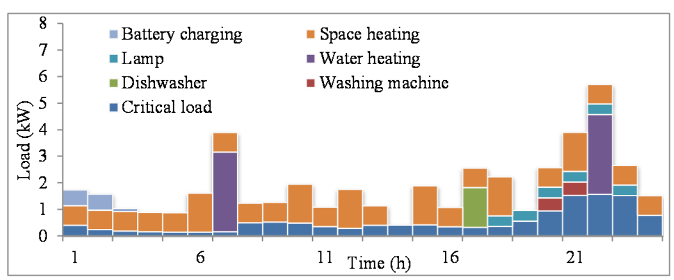
b) CPP



c) RTP



d) EDRP



e) I/C services

Fig. 3. Household load in different cases.

As can be seen in Fig. 3b, the CPP reduces the peak-to-valley factor too. The HEM has preferred to move the operation time of all residential appliances out of the critical peak hours, despite the high dissatisfaction cost of water heating.

On the opposite of TOU, CPP compels the washing machine to work on 6 PM and7 PM, since the CPP tariff has been double of the TOU in critical peak hours. In addition, the battery has been charged once. According to Fig. 4, the battery has discharged at 10 AM and 12 AM to inject some energy to home.

According to Fig. 3c, by choosing RTP the HEM arrange the operation time of water heating and dishwasher similar to the case of choosing TOU. Also, the lamps are only on at 18:00 when the price is low. However, battery charging is changed due to the hourly dynamic tariffs in the RTP, compared to TOU. According to Fig. 3d, EDRP is the only DR program that compels the HEM to move the operation time of water heating to out of the critical peak. However, this causes that a demand peak occurs at hour 23:00.

By choosing I/C services, the operation time of dishwasher is shifted from the critical peak to peak, since the curtailment of load under this program in peak period is half the critical peak period. It should be noted that in CPP and both incentive-based DR programs, the battery is charged only once a day in the low-load hours.

The common point of these three DR programs is the high focus of them on the critical peak period. Therefore, the battery is charged during the day and injects the power to the home only at the critical peak hours. While, in the TOU program, the battery is charged twice a day and injects the power to the home at both peak and critical peak periods.

The consumer's cost in different DR strategies is compared in Fig. 5. As it is shown, the CPP enforces the highest cost to the consumers, however the presented HEM reduces it around 40 %. TOU and RTP are the DR strategies that force high costs to the consumers that using the proposed model can moderate it.

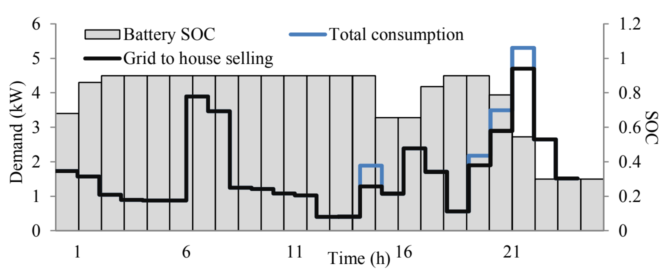


Fig. 4. The battery performance in TOU program

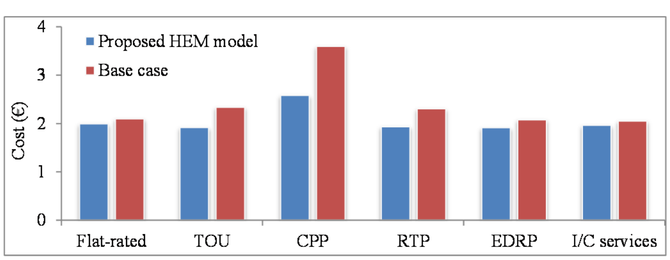


Fig. 5. Customer's cost in different DRPs.

V. CONCLUSIONS

This paper proposed a model of HEM to minimize the customer's cost in different DR strategies. It can guarantee also habitants' satisfaction and ensure operational constraints of battery and residential appliances. Numerical studies revealed that the proposed method could have noticeable influence on the operational profile of HEM systems in different price-based and incentive-based DR strategies. The results showed that by employing the presented HEM, the end-user's cost might be decreased up to 40%.

ACKNOWLEDGMENT

This work was supported by FEDER funds through COMPETE 2020 and by Portuguese funds through FCT, under Projects SAICT-PAC/0004/2015 - POCI-01-0145-FEDER-016434, POCI-01-0145-FEDER-006961, UID/EEA/50014/2013, UID/CEC/50021/2013, and UID/EMS/00151/2013. Also, the research leading to these results has received funding from the EU Seventh Framework Programme FP7/2007-2013 under grant agreement no. 309048.

REFERENCES

[1] M. H. Shoreh, et al. "A survey of industrial applications of Demand Response," Electric Power Systems Research, vol. 141, pp. 31-49, 2016.

[2] C. W. Gellings, The smart grid: Enabling energy efficiency and demand response. Boca Raton: CRC Press, 2009.

[3] Z. Chen, L. Wu, and Y. Fu, "Real-time price-based demand response management for residential appliances via stochastic optimization and robust optimization," Smart Grid, IEEE Transactions on, vol. 3, no. 4, pp. 1822–1831, Dec 2012.

[4] S. Shao, M. Pipattanasomporn, and S. Rahman, "Demand response as a load shaping tool in an intelligent grid with electric vehicles," Smart Grid, IEEE Transactions on, vol. 2, no. 4, pp. 624–631, Dec 2011.

[5] A. Khodaei, M. Shahidehpour, and S. Bahramirad, "Scuc with hourly demand response considering intertemporal load characteristics," Smart Grid, IEEE Transactions on, vol. 2, no. 3, pp. 564–571, Sept 2011.

[6] C. Halford and R. Boehm, "Modeling of phase change material peak load shifting," Energy and Buildings, vol. 39, no. 3, pp. 298 – 305, 2007.

[7] C.-L. Su and D. Kirschen, "Quantifying the effect of demand response on electricity markets," Power Systems, IEEE Transactions on, vol. 24, no. 3, pp. 1199–1207, Aug 2009.

[8] K. Tsui and S. Chan, "Demand response optimization for smart home scheduling under real-time pricing," Smart Grid, IEEE Transactions on, vol. 3, no. 4, pp. 1812–1821, Dec 2012.

[9] M. Pipattanasomporn, M. Kuzlu, and S. Rahman, "An algorithm for intelligent home energy management and demand response analysis," Smart Grid, IEEE Transactions on, vol. 3, no. 4, pp. 2166–2173, Dec 2012.

[10] M. Kuzlu, M. Pipattanasomporn, and S. Rahman, "Hardware demonstration of a home energy management system for demand response applications," Smart Grid, IEEE Transactions on, vol. 3, no. 4, pp. 1704–1711, Dec 2012.

[11] S. Shao, M. Pipattanasomporn, and S. Rahman, "Grid integration of electric vehicles and demand response with customer choice," Smart Grid, IEEE Transactions on, vol. 3, no. 1, pp. 543–550, March 2012.

[12] M. Albadi and E. El-Saadany, "A summary of demand response in electricity markets," Electric Power Systems Research, vol. 78, no. 11, pp. 1989 – 1996, 2008.

[13] H.A. Aalami, M. P. Moghaddam, and G. R. Yousefi "Demand response modeling considering interruptible/curtailable loads and capacity market programs," Applied Energy, vol. 87, no. 1, pp. 243-250, 2010.

[14] C. O. Adika, L. Wang, "Smart charging and appliance scheduling approaches to demand side management, International Journal of Electrical Power and Energy Systems, vol. 57, pp. 232-240, 2014.

[15] M. Shafie-khah, et al. "Optimal behavior of responsive residential demand considering hybrid phase change materials," Applied Energy, vol. 163, pp. 81-92, 2016.