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Scheduling of Residential Multiclass Appliances in Smart Homes usingV2H capability of Electric Vehicle

Zahra Sabouri[1], Mahmoodreza Haghifam[2]

[1]Department of Industrial Engineering, South Tehran Branch, Islamic Azad University, Tehran, Iran, zahra.sabouri@yahoo.com
[2]Faculty of Electrical & Computer Engineering, Tarbiat Modares University, Tehran, Iran, haghifam@modares.ac.ir

Abstract

With the aim of reducing cost of electricity consumption and peak load reduction, tools requirement for better managing electricity consumption have become inevitable in recent years. Smart home has some equipment which are controllable and this ability is used for increasing comfort and minimizing electricity cost for residence. As a key component of smart home , Electric Vehicle(EV) ,increase the ability of consumers in participating in Demand Response (DR) programs. One of the key issues raised in this aim is to present a way for entry and exit of this equipment to the network in order to reduce electricity cost for customer. So in this article 5 set of appliances and V2H capability of EV together with Time of Use (TOU)-pricing signal based DR strategy are all combined in a single Home Energy Management (HEM) system for the first time. A Mixed-Integer Linear Programming (MILP) is used for this purpose.

Keywords: Home energy management, Demand response, Electric vehicle, Smart home.
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1. Introduction

Residential areas are responsible for nearly 40% of the energy consumption and Carbon Oxide (CO) emission in developed countries. These areas are known to have significant potential for energy and cost savings, as well as load classified [1]. By increasing energy demands of the residential consumption, governments are making efforts to find a way for cutting CO emissions raised by using fuel and be helpful to meet some of the long-term challenges in ensuring an affordable, secure, and sustainable energy supply. Demand Side Management (DSM), smart grid smart home and EVs, open some way for reducing electricity consumption and peak power. The goal of demand response is to benefit both consumers and utilities. Smart grid customers find more opportunity for participating in DR programs and EVs increase customers' ability of participating in DR programs with their V2H ability. By use of elasticity of energy consumption level factor appliances can be classified into two general groups: elastic appliances and inelastic appliances. In addition, each of these two according to some features such as the way of consuming energy and operation can be divided in to sub-sets.

A lot of studies have been done on smart home in the recent year. [2],[3] develop some optimization algorithm for better operation of smart home using Time Of Use (TOU) strategy.[4] Does real-time scheduling for appliances to participate in DR programs. In [5] electricity consumption behaviour of household is studied under different pricing schemes. [6] Introduces a Mixed Integer Linear Programing of HEM by considering EV by V2H ability and classifies appliances in two sets of thermostatically and none thermostatically controllable appliances. [7] presents an algorithm for scheduling thermostatically appliances under user preference and price signal. [8] and [9] present a more complete model for classifying appliances in smart homes but they do not consider EVs. [10] studies the impact of EV on electricity costs but does not consider appliance classification.

Here we introduce a model for smart homes in which the effects of both classification of appliance and EV, for real-time pricing based DR, on electricity cost of costumers is studied

2. EV Modeling and Appliances Set

Here we categorize appliances in 5 groups depending on their characteristics of consuming energy or operation and present a mathematical model for them. In addition an EV models with V2H ability is presented too.

A) EV modelling

Equation (1) demonstrates that the power provided by discharging EV battery can be used for appliances need ($\mathrm{DE_{EV}}$ is discharging efficiency of the EV and $\mathrm{T^a}$, is arrival time of EV to home and Departure of EV and $\mathrm{T^d}$ is departure time of EV from home). Constraint (2) and (3) shows limitation for charging and discharging of EV battery ($\mathrm{CR_{EV}}$ is charging rate of the EV, $\mathrm{u_t^{EV}}$ is Binary variable for EV charging, $\mathrm{DR_{EV}}$ is Discharging rate of the EV) .State of energy (SOE) in every sub-interval can be calculated by (4).Estate of energy of EV when it arrived at home is considered as initial ESS for EV as described by (5). Equation (6) represent that all the variables related to EV modelling are zero when EV is not in home.

$$P_t^{EV.used} = P_t^{EV.dis.}.DE_{EV}.\forall_t \in [T^a - T^d] \quad (1)$$

$$P_t^{EV.ch} \le CR_{EV}.u_t^{EV}.\forall_t \in [T^a - T^d] \quad (2)$$

$$P_t^{EV.ch} \le DR_{EV}.(1 - u_t^{EV}).\forall_t \in [T^a - T^d] \quad (3)$$

$$SOE_t^{EV} = SOE_{t-1}^{EV} + CE_{EV}.\frac{P_t^{EV.ch}}{\Delta T} - \frac{P_t^{EV.dis}}{\Delta T}.\forall t \in [T^a - T^d] \quad (4)$$

$$SOE_t^{EV} = SOE^{EV.ini}. \ if \ t = T^a \quad (5)$$

$$SOE_t^{EV} = P_t^{EV.used} = P_t^{EV.dis} = P_t^{EV.ch} = 0, \forall t \notin [T^a - T^d] \quad (6)$$

B) Appliances modelling

By using of elasticity of energy consumption level factor, appliances can be classified into two general groups: elastic appliances and inelastic appliances. In addition each of these two groups can be divided into sub-sets according to some feature such as the way for consuming energy and operation [11].

Elastic appliances

Elastic appliances can flexibly adjust their energy consumption level. These appliances are divided into three sub set according to whether their performance in each sub-interval is affected by only the current energy consumption or the previous energy consumption in their operation period is effective too. So three subsets for elastic appliances are considered and modelled here.

- *Elastic appliances with memory less property*

These appliances are those which user satisfaction from their performance depends on their performances on that sub-interval so they should kept on during their schedulable time. For modelling this kind of appliances the equations below are used. e_a^{max},e_a^{min}, in (7) denote the maximum and minimum consumption for appliance a . In addition, each appliance a has its utility function, $U_a(e_a)$, which is defined as (8)

$$e_a^{min} \le e_a^t \le e_a^{max} \quad (7)$$

$$U_a(e_a) = \sum_{t \in T_a} U_a^t(e_a^t) \quad , \quad \forall_a \in A_{EML} \quad (8)$$

- *Elastic appliances with full memory property*

User satisfaction from appliance performance in this group is from their total work on all sub-intervals. For example appliances such as battery charger can be classified in this group. Each appliance in this set also has the maximum and minimum values for its energy consumption (9). Utility function is described in (10).

$$e_a^{min} \le e_a^t \le e_a^{max}, \ \forall_a \in A_{EFM} \quad (9)$$

$$U_a(e_a) = U_a\left(\sum_{t \in T_a} e_a^t\right) \quad , \quad \forall_a \in A_{EFM} \quad (10)$$

- *Elastic appliances with partial memory property*

Similar to what was said about two previous models here we have a maximum and minimum energy consumption limit for appliances in this group as you can see in (11). Satisfaction of a user from appliance performance in this group at each sub-interval depends not only on the current energy consumption level at that sub-interval but also the energy consumption at previous sub-intervals with different weights (12). And Thermostatically-controlled appliances such as electric heaters, air conditioners, and refrigerators can be classified into this set. For example, the thermal dynamic model of electric heater a can be represented as (13) (see [12, Sec. II-A], [13, Sec. 3.4.2] for details):

$$e_a^{min} \le e_a^t \le e_a^{max} \quad \forall_t \in T_a \quad , \quad (11)$$

$$U_a(e_a) = \sum_{t \in T_a} U_a^t\left(\theta_{a,in}^t(e_a^t)\right) \quad (12)$$

$$\theta_{a,in}^t(e_a^t) = \epsilon_a \theta_{a.in}^{t-1}(e_a^{t-1}) + (1 - \epsilon_a)(w_{a,out}^t + k_a^t e_a^t) \quad (13)$$

Inelastic appliances

Inelastic appliances consume fixed energy at each sub-interval if they are on. And interruptible operation is a factor which is used for dividing inelastic appliances in two sub set.

- *Inelastic Appliances with Interruptible Operation*

Some inelastic appliances such as vacuum cleaners can be intermittently turned on and off in their scheduled time. We assume that for each appliance a, its user has the requirement mentioned in (14)(M_a is Minimum performance threshold of appliance a during entire time interval) (15) declare that the appliance use fixed energy (E_a) when it is on.

$$\sum e_a(t) \geq M_a \quad (14)$$

$$e_a^t \in \{0 , E_a\} \quad (15)$$

- *Inelastic Appliances with Uninterruptible Operation*

These kind of appliances have uninterruptible operation such as washing machine which consume fixed energy in each sub interval and as it start to work , it should kept on till finishing its work. Constraint and equation used for this set is as follow:

$$\sum_{t=S_a}^{f_{a-[M_a/E_a]}} y_a^t = 1 \quad (16)$$

$$e_a^h \geq E_a y_a^t \quad , \quad \forall_h \in [t, t + [M_a/E_a] - 1] \quad (17)$$

Equation (16) represents that appliance A should start its operation during its schedulable interval (y_a^t is Integer variable that indicates whether the operation of appliance a starts at sub-interval t). The constrain in (17) represents that once appliance a starts its operation at sub-interval t, it should be on at least next $[\frac{M_a}{E_a}]$ sub-intervals continuously.

C) Objective Function

Objective function here is minimizing electricity cost for customer and it expressed as fallow:

$$Minimize\ Of = \sum_t (E_t^{grid} . \mu_t^{buy}) \quad (18)$$

E_t^{grid} is energy which is bought from grid and μ_t^{buy} is price for unit energy consumption at sub-interval *t*. Here we want to decrease the total cost for customers by using EV in V2H operation mode and the ability for adjusting energy consumption level in elastic appliances and shifting the switching time of inelastic appliances.

3. Numerical Results

To evaluate the impact of classifying appliances and use of EV with V2H operation mode on electricity cost for customers, we consider a smart home with 6 appliances and an EV and use the Constraint and equation which was mentioned at part 2. We use data from [10], [11] for EV and appliances. We assume that the entire scheduling time interval consists of 96 sub-intervals (every interval 15 min), electricity price in 24h (96 sub-interval) is provided in Fig.1.[14]

For solving Mixed Integer Linear Programming (MILP) problem here the Branch and Bond method is used in MATLAB. Three scenarios with their result are as below:

First- we optimized consumption of appliances and evaluate the importance of appliances classifying smart home. In this scenario we consider customer who willing to charge EV immediately after arriving at home. As satisfaction of operation in first group of appliances is affected by its operation in each sub-interval it should be on during its schedulable interval but for minimizing electricity bill it tries to consume a little amount of energy in expensive sub-interval (see fig.2 (a)). Fig.2 (b) shows the consumption management for appliance in second group, as the performance of these group of appliances is affected by its total energy consumption it tries to consume its energy as much as possible in cheap sub-interval .in fig.2(c) we show the consumption management for appliances in third group, and fig.2 (d) shows the temperature variation it can be seen that according to temperature variation. appliances in this group consume more energy while maintaining higher temperature.Fig.2(e &f) shows the energy consumption management for inelastic appliances as it can be seen these appliances try to consume their maximum energy in cheap sub-intervals. However, the interruptible appliance can be intermittently tuned on and off; while the uninterruptible appliance should be kept on continuously once it is on. In this scenario EV charging start as soon as EV arrival at 6pm regardless of electricity cost. Fig.3 (a) shows ESS for EV. Fig. 3(b) shows the total power bout from the grid and then the electricity cost for customer become 89 [cent /kW] in this scenario.

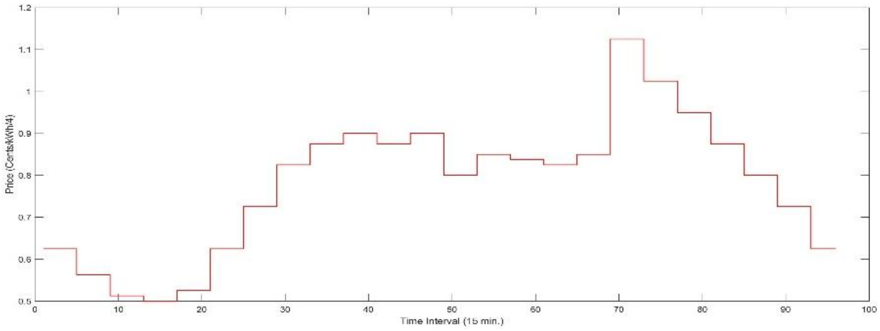

Fig. 1. Electricity price

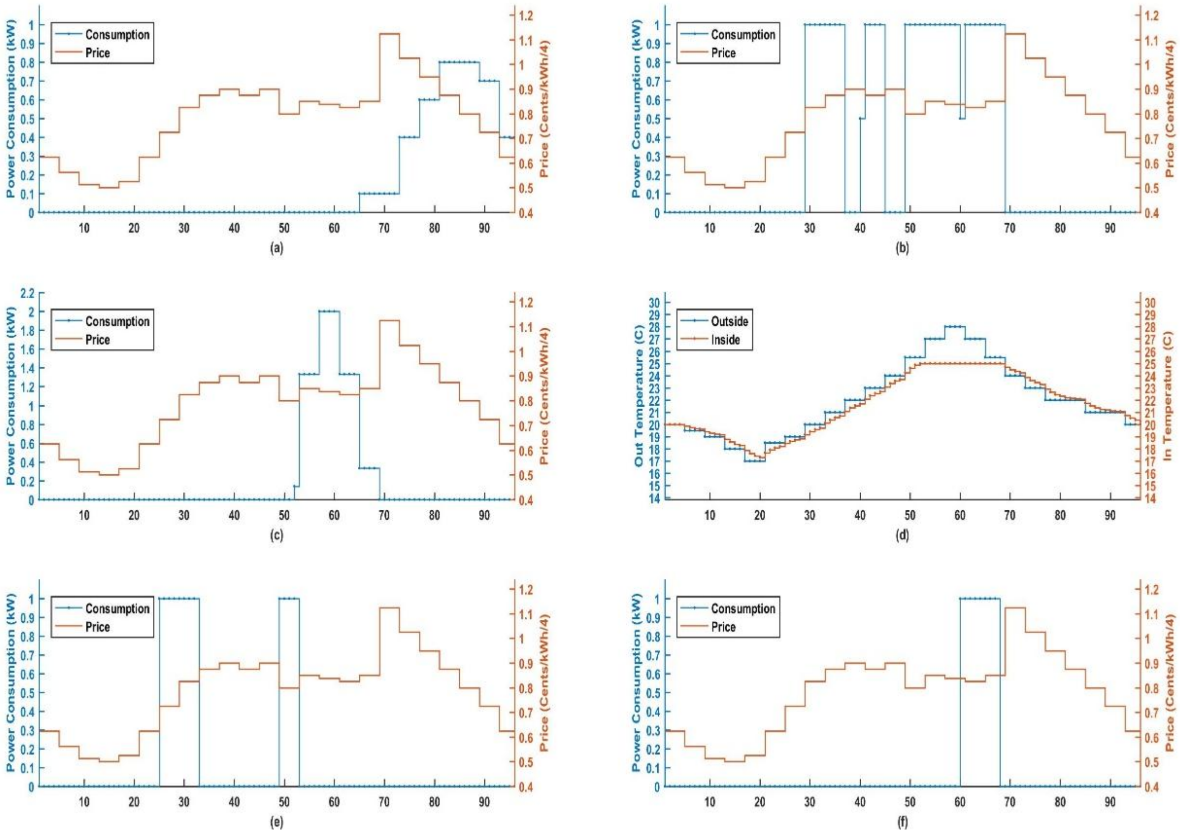

Fig. 2. Appliances consumption scheduling, (a) set1 ,(b)set2, (c)set3 (d) temperature (e) set4 ,(f) set5

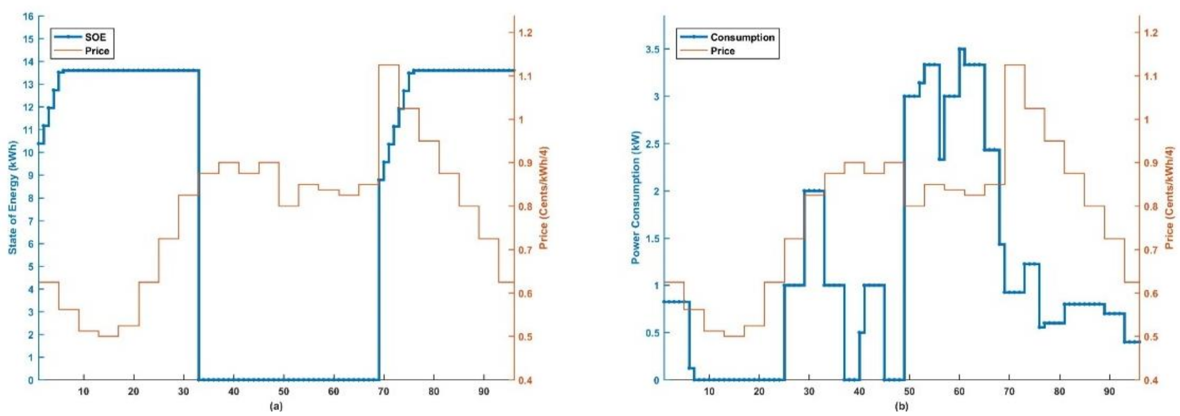

Fig. 3. (a) Estate of energy variation for EV; (b) total power consumption in first scenario

Second- In this scenario we optimized consumption of appliances and we consider customer who willing to charge their EV with lower price. You can see appliance load scheduling for different set in fig.4. The ESS for EV is shown in fig.5 (a) it can be seen that EV charged at cheap sub-interval. Total bought power from grid is shown in fig.5 (b) Here with optimal charging for EV the electricity cost for customer decreased to 81.94 cent.

Third- we optimized consumption of appliances in different set and consider EV with V2H ability. You can see appliance load scheduling for different set in fig.9. As you can see in fig.10 which shows ESS of EV, as soon as the EV owner arrives home at 6 P.M., the EV is plugged-in and the household power demand is supplied by the EV and as fig.7 (a) shows the EV is charged in chip sub-interval periods. Fig.7 (b) shows total energy consumption in this case. Total electricity cost in this scenario becomes 76[cent /Kw].

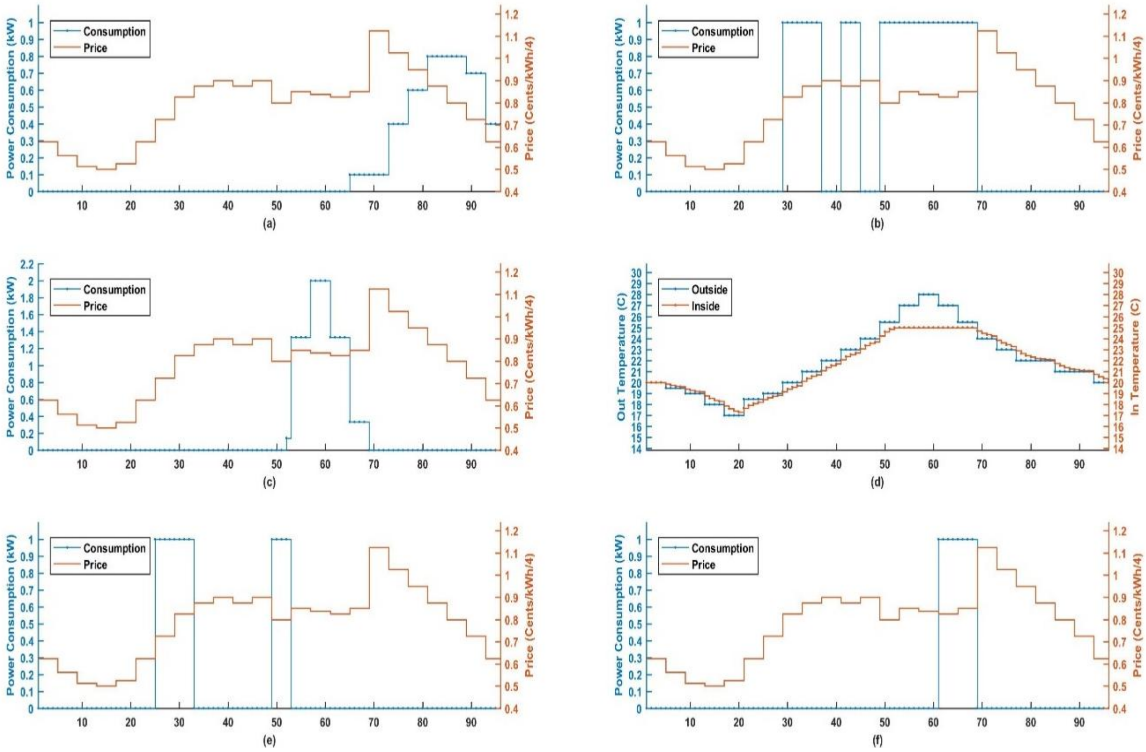

Fig. 4. Appliances consumption scheduling, (a) set1 ,(b)set2, (c)set3 (d) temperature (e) set4 ,(f) set5

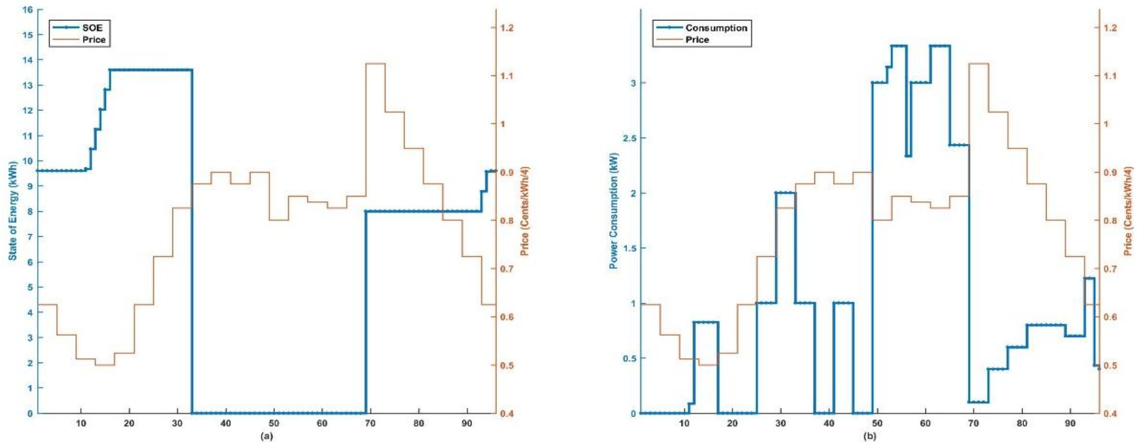

Fig. 5. (a) Estate of energy variation for EV; (b) Total power consumption

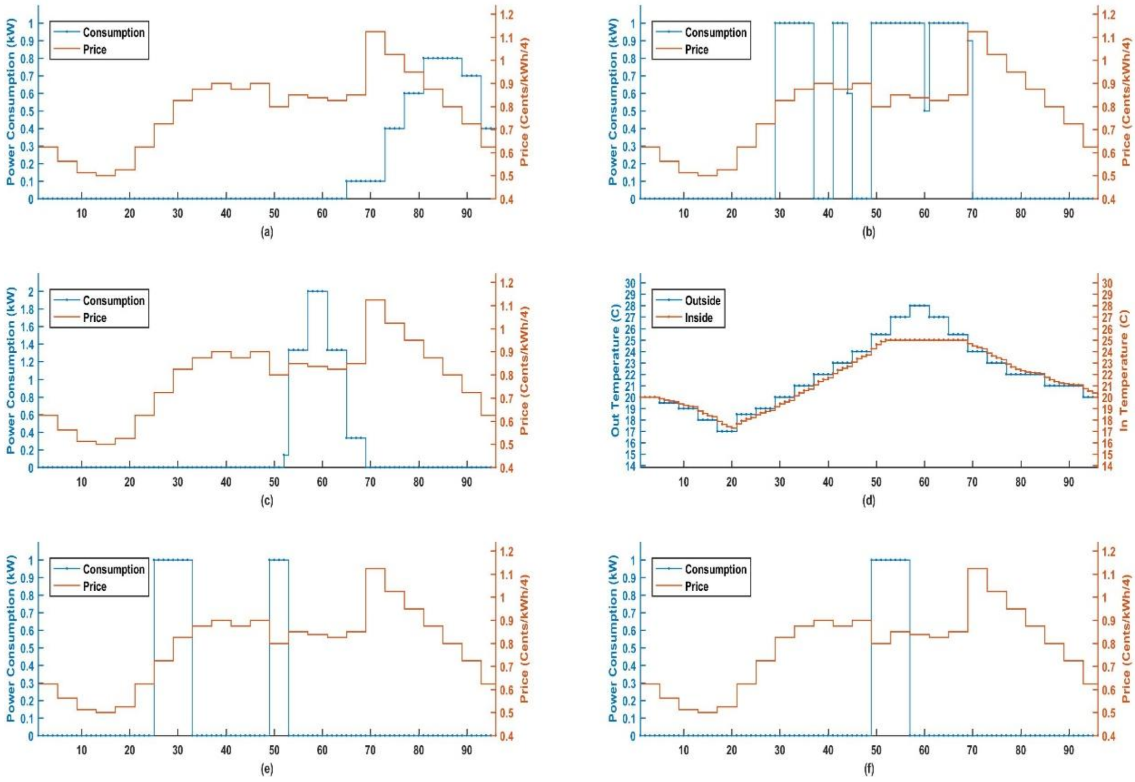

Fig. 6. Appliances consumption scheduling, (a) set1 ,(b)set2, (c)set3 (d) temperature (e) set4 ,(f) set5

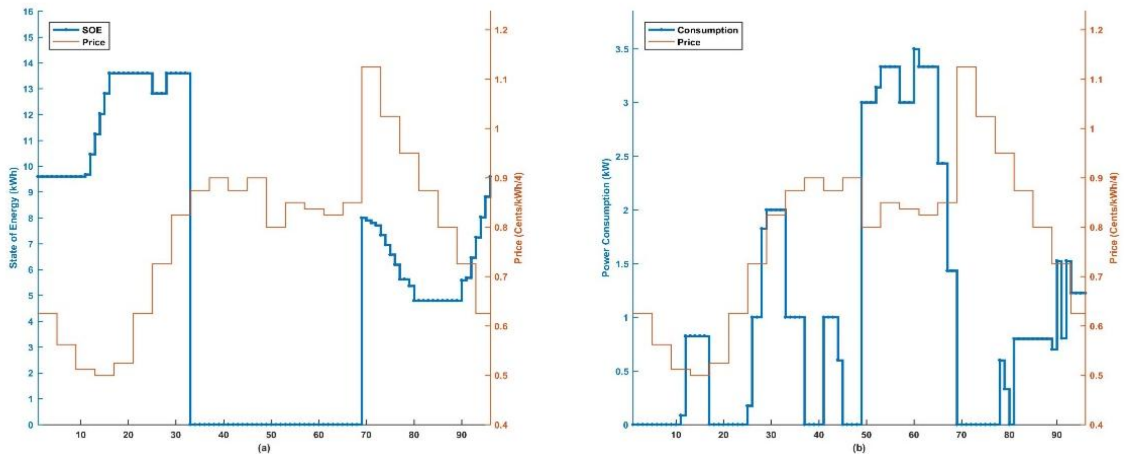

Fig. 7. (a) Estate of energy variation for EV; (b) Total power consumption

4. Conclusion

In this paper as the main contribution to the literature on smart home operation, the effect of classifying appliances and V2H ability for EV on electricity bill was evaluated under TOU-pricing based DR strategy using a MILP framework-based modelling of a HEM structure. A complete real-time pricing signal and user preferences were assumed to be known. After examining several scenarios as was shown in previous section, by adjusting energy consumption level in elastic appliances (consuming a few amount of energy in expensive sub-interval and consume more in lower price period) and shifting the switching time for inelastic appliances (working in lower price period) and even by using the energy stored in EV battery instead of buying from utility in expensive sub-interval, we could decrease the electricity bill for customers. For future work we will evaluate the effect of peak power limiting and two way connection of EV too.

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