Applying Energy Consumption Schedule and Comparing It with Load Shifting Technique in Residential Load

Amira M. Attia, Karim H. Youssef, Nabil H. Abbasy

Abstract**—**Energy consumption schedule (ECS) technique shifts usage of loads from on peak hours and redistributes them throughout the day according to residents' operating time preferences. This technique is used as form of indirect control from utility to improve the load curve and hence its load factor and reduce customer's total electric bill as well. Similarly, load shifting technique achieves ECS purposes but as direct control form applied from utility. In this paper, ECS is simulated twice as optimal constrained mathematical formula, solved by using CVX program in MATLAB® R2013b. First, it is utilized for single residential building with ten apartments to determine max allowable energy consumption per hour for each residential apartment. Then, it is used for single apartment with number of shiftable domestic devices, where operating schedule is deduced using previous simulation output results as constraints. The paper ends by giving differences between ECS technique and load shifting technique via literature and simulation. Based on results assessment, it will be shown whether using ECS or load shifting is more beneficial to both customer and utility.

Keywords**—**Energy consumption schedule, load shifting technique, comparison.

NOMENCLATURE

a_u / a_a	Beginning time of consuming electric energy in ECS per unit / or starting time of appliance.
b_u / b_a	Ending time of electric consumption in ECS per unit for single day / ending time of appliance operation.
C^h	Cost of energy consumption per hour, pricing signal information used is Daily Ahead Price (DAP) ($/h).
E_u / E_a	Total energy consumed per unit in ECS / or total energy consumed per appliance (kWh).
Pvalue_u^h	Limit value set by utility to prevent power load to exceed it during peak hours in load shifting = 1.5 kW.
Pold_u^h	Load demand before applying load shifting, it is taken from BEopt load profile.
Pnew_u^h	New load demand resulted from applying load shifting technique.
P_m^u	Peak power demand of each apartment u at m after applying load shifting technique.
P_u^h	Power demand of each apartment u at time interval h. after applying load shifting technique.
${s_u}^h$/ ${s_a}^h$	Resulted ECS for each unit for a residential building / or shiftable appliances in residential apartment (kWh).
x_u / x_a	Min power level or stand-by power that accumulated in each unit due to having domestic devices in stand-by mode (kW) in ECS.
y_u / y_a	Max power level each unit must not exceed it per time slot (kW) in ECS. Or max power consumed by appliance,
A	Total number of appliances per unit, in the model A = 5.
$Emax$	Max total energy consumption required in ECS for all units per hour. Utility sets its value, in the model $Emax$ = 5 kWh.
H	Total number of time intervals in hours = 24.
M	Max total energy consumption of operating appliances per hour = ${s_{u1}}^h$, h ∈ {1, 24}.
To	Beginning of time interval which will be 1 after midnight.
TK	Peak hour time beginning which will be 14 hr at 14th time interval.
TH	Peak hour time ending which will be 23 hr at 23th time interval.
TD	Ending of time interval which will be 24 hr at 24th time interval.
U	Number of residential units in one building = 10.
a	∈ {1, A} number of appliances.
h	∈ {1, 24} number of time intervals.
t_h	Time duration of each time interval h = 1 hour.
u	∈ {1, 10} number of apartments.

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I. INTRODUCTION

ENERGY Consumption Schedule (ECS) or Energy Management Controller [1], [2] is one of demand side management (DSM) techniques, which aim to achieve DSM goals [3]. It is form of indirect load control, that permits consumers as residents in residential areas to control their home appliances operations and therefore its energy consumption based on signal pricing received directly from utility via internet [4]. ECS is mostly applicable in residential sector, which is used to schedule domestic appliances. It shifts home appliances from on peak hours into off peaks, to reduce peak load as well as global peak reduction [5].

To run ECS algorithm, advanced smart meters and two-way communication are needed [6]. Smart meters are essential for data exchange, that occurs between utility and customer. Such price signals are sent by utility to customer through smart meters via proper communication means. Also, customers sent their domestic appliances' characteristics; actuation time, operation length, deadline, and consumption profile through smart meters via available communication means. Inside smart meters there is ECS program which gives optimal operating schedule for home devices in order to reduce peak demand [5]. To run ECS algorithm, the data needed are sent from both utility and customer as well as the resulted optimal schedule, so two-way communication is demanded. Wireless technologies such as Wi-Fi, ZigBee, Bluetooth, Infrared, etc. are examples that can be implemented in smart grid infrastructure for communication purpose through computer network [1][6].

Energy consumption management architecture inside home is as shown in Fig. 1. It is consisting of advanced metering infrastructure and wireless technologies for communication targets. Advanced metering infrastructure is integrated systems of smart meters, that connect utility to the customer and vice versa via internet network. As shown in the figure, the dashed line represents information flow, while solid line represents power flow. Starting from supply or utility information about pricing, signals are sent to customer through smart meters via Wi-Fi for instance. Also, residents' preferences about their home appliances are sent as well through smart meter. Energy management controller or ECS is implemented inside smart meter that runs to give optimal domestic appliances operation schedule, that will result in reduction to both peak load demand and electricity bill. ECS helps to estimate schedule for storing and using generated electric energy from renewable sources [1].

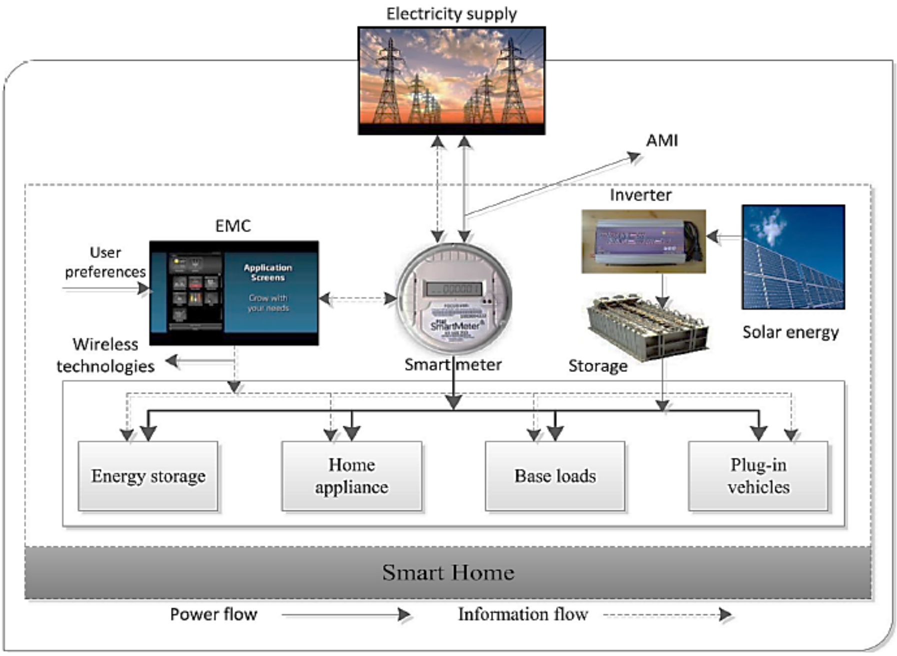

Fig. 1 Energy management architecture

This paper aims at exploiting the merits of having smart meter for whole residential building along with smart meter implemented inside each apartment. The presence of smart meter at the entrance of building results in computing the max energy consumption allowed per hour instead being set directly by utility. Then, the results are used as constraint to estimate operating schedule for home devices for each residential unit. The paper is organized as follows. Section II summarizes the advantages and disadvantages of ECS. Section III simulates mathematical optimal formula of ECS. Effect of having computed max energy consumption per hour and fixed value per hour is studied as well. Section IV compares the results from applying load shifting technique and ECS. Conclusions are discussed in Section V.

II. Advantages and Disadvantages of ECS

ECS is a constrained mathematical problem, that is implemented in controllers or smart meters. Depending on objective function in mathematical problem, the benefits of resulted operating schedule will differ from one to another. There are different types of objective functions used for estimating domestic appliances operating schedule; cost minimization aims for reduction in electricity bill, scheduling preferences maximization cares more about comfort of customers regarding appliances' operation time schedules, climatic comfort maximization controls heating, cooling and ventilation depending on weather and customer's comfort [7], peak to average minimization, and peak load minimization [8].

ECS causes reduction in both peak demand and electricity bill among other benefits or features that are summarized in the following points [9]:

- Reduction in peak demand or energy output during peak time.
- Reshaping power load requirement.
- Feasibility of applying ECS in any computing devices such as controllers, mobile devices, high-capacity computing servers.
- Scheduling is processed in real time operating system, which manages execution of tasks on processors under time constraint.
- Achieves comfort in appliances operation for customers.
- Reduction in peak average ratio; when power profile of each apartment is added up, it may result in higher peak power demand than average power, therefore ECS reduces it.
- Reduction in energy cost.

– Charges each user's daily electricity.

However, ECS can have some disadvantages, such as:

– It cannot reduce total energy consumption significantly.
– To control and mange group of unit schedulers it extends scheduling time and makes system more complex [9].
– Since all ECS data transmitted via internet, it is most likely to be compromised to cyber-attacks (load attacks).
– Fabricated information can be triggered especially about prices, which lead to changing energy consumption program and hence load profiles.
– Smart meters can face intrusion that causes unauthorized modification or access to normal operations of smart meters [4].
– The expenses of having and repairing sensors and smart meters.

III. ECS Simulation

The model used to estimate ECS, is a game theoretic model-based optimization constrained technique [2]. The objective function is solved by using CVX program implemented in MATLAB® (R2013b). Simulation is run in two parts; first the whole residential building is simulated where number of buildings is the players, and daily schedule of apartments is the strategies. Then, units or apartments are simulated where number of users is the players, and daily schedule for domestic appliances is the strategies. The aim of the first simulation is to determine the max allowable energy consumption per hour that will be used as constrained in the second simulation.

A. ECS for Residential Building

Daily ECS for a whole residential building is estimated by using the following mathematical form [8][10].

$$\text{Min} \sum_{h=1}^{H} C^h * \left(\sum_{u=1}^{U} s_u{}^h\right), \quad (1)$$

subject to

$$\sum_{h=a_u}^{b_u} s_u{}^h = E_u \qquad \forall\, u \in U \quad (2)$$

$$x_u \le s_u{}^h \le y_u \qquad \forall\, u \in U,\ h \in [a_u, b_u] \quad (3)$$

$$\sum_{u=1}^{U} s_u{}^h \le Emax \qquad \forall\ h \in H \quad (4)$$

Main smart meter is installed at the entrance of residential building, to estimate ECS for each unit. Using game theoretic optimal problem residential building acts as players, while units act as strategies. The problem depends on the following parameters; price signal information, total energy consumption per unit, min and max power level, and max total energy consumption per hour.

Price information C^h is sent by utility or aggregator that controls several residential sectors through smart meter via internet to residential building. Price signals are dynamic that vary hourly through day, from dynamic time differentiated pricing programs; real time pricing (RTP), day ahead pricing (DAP), time of use (TOU), and critical peak pricing (CPP) [11]. In this model, DAP is implemented instead of using TOU [1]. Both of DAP and TOU are known in advance to customers; however, DAP is fixed through day while TOU through month or season, so for better implementation DAP is more suitable than TOU pricing. By using DAP data in Fig. 2, which is taken from New York ISO website (NYISO) [12], the peak hours will have high prices to get optimal ECS that will reduce total electric bill.

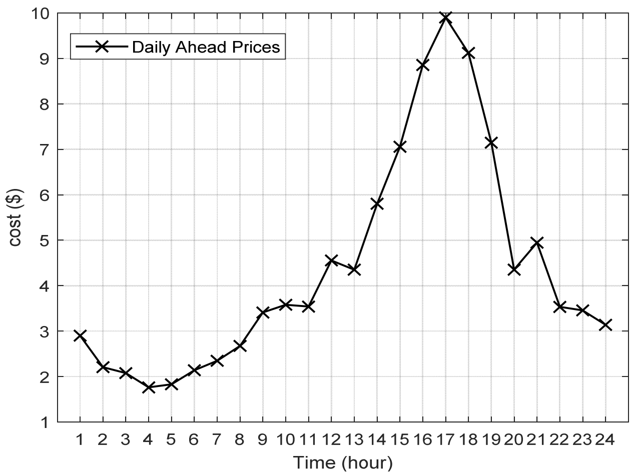

Fig. 2 DAP ($/h) according to New York ISO website

Total energy consumption per unit E_u is extracted from BEopt software, which is total energy used by each unit. The appliances in each unit are divided into shiftable and unshiftable, therefore the extracted E_u is accumulation of shiftable appliances' power consumption. Min energy level parameter x_u for each unit is accumulated from leaving appliances in stand-by mode e.g. televisions, audio players, telephone answering, lap-top computers, printers, microwave ovens, conventional electrical ovens, etc. The estimated energy consumed from devices on standby mode ranges 0.6 kWh to 5 kWh per day [13]. In this model, min energy consumptions used for each unit are extracted from BEopt software, by taking the least energy consumption from each unit and adding 0.03 kWh. Max energy level y_u is set by utility. In this model, its value has been extracted from BEopt software by selecting the highest energy consumptions and subtract 0.02 kWh from them. Max total energy consumption per hour $Emax$ is set by utility or aggregator as well, in this model $Emax$ value is 5 kWh.

After running simulation by using CVX program for time starts at the beginning of the day a_u= 1:00 till the end of day b_u= 24:00 in the first of August with max energy consumption per hour = 5 kWh, load factor improves from 0.56 to 0.7. The resulted schedule is matrix with 10 rows for total number of units and 24 columns for number of hours per day. The impact of performing ECS for whole residential building is shown in Fig. 3, that reduces peak demand and energy consumption during peak hours due to usage of DAP.

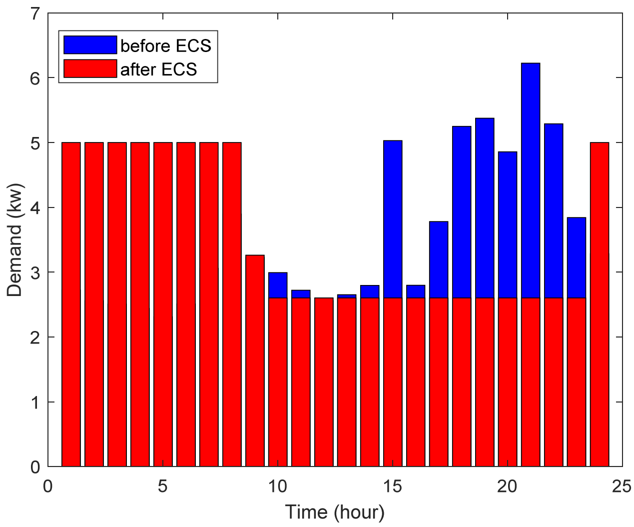

Fig. 3 Applying ECS for whole residential building

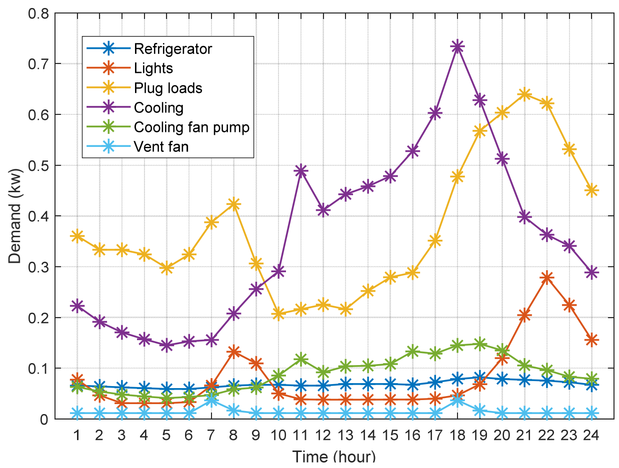

Fig. 4 Non-shiftable appliances data

B. ECS for Single Residential Unit

Operation schedule for appliances is estimated depending on either the appliances are shiftable or not and allowed max total energy consumption per hour for single unit. From the previous simulation, the resulted ECS ${s_{u1}}^{h}$ per unit is used to determine maximum allowed total energy consumption for devices per hour, which the total energy consumption per hour resulted from simulation is for shiftable domestic appliances that are operated during day and it is sent via internet to smart meter in apartment. So domestic appliances are separated into two groups; manageable (shiftable) loads that ECS algorithm is applied onto and non-manageable (unshiftable) loads. From unshiftable appliances built in BEopt software including refrigerator, central air conditioner, lighting, and plug loads such as (TV, laptops, phones) [14], their demand per hour is shown in Fig. 4, while shiftable appliances used in BEopt software that are implemented as resident's preferences in smart meter are washing machine, clothes dryer, cooking range, and dishwasher [14]. The same mathematical optimal problem is used to get the operating schedule for domestic appliances instead of apartments, the residents in this game theoretic problem act as players, while appliances act as strategies.

Aim of objective function is to minimize customer's total electric bill.

$$\text{Min} \sum_{h=1}^{H} C^h * \left(\sum_{a=1}^{A} {s_a}^h\right) \quad (5)$$

subject to

$$\sum_{h=a_a}^{b_a} {s_a}^h = E_a , \forall\, a \in A \quad (6)$$

$$x_a \leq {s_a}^h \leq y_a \quad \forall\, a \in A,\ h \in [a_a, b_a] \quad (7)$$

$${s_a}^h = 0,\ \forall\, a \in A,\ h \notin [a_a, b_a] \quad (8)$$

$$\sum_{a=1}^{A} {s_a}^h \leq M , \forall\ h \in H \quad (9)$$

TABLE I
SHIFTABLE APPLIANCES DATA

Appliances A = 5	**Total Energy Consumption E_a**	**Start Time a_a**	**End Time b_a**	**Min Power Level x_a**	**Max Power Level y_a**
Cooking range	1.228	7	23	0.0514	0.14
Washing machine1	0.3	10	11	0	0.3
Washing machine2	0.1577	17	19	0	0.1
Dish washer morning	0.846	9	13	0	0.3
Dish washer evening	1.46	18	23	0	0.54

In single unit, appliances that can be scheduled are cooking range, washing machine, and dishwasher such that washing machine and dishwasher are operated twice per day. There are two objective functions used for scheduling domestic devices; the first one aims to minimize total electric bill regardless of discomfort that may cause residents from increasing waiting time till appliances operate, the second makes trade-off between reduction of both electric bill and waiting time. The objective function used in this section is similar to the function used for estimating ECS for residential building with similar DAP signal, which reduces total electric bill only. After residents input their preferred preferences in their smart meter device as shown in Table I, ECS is conducted between time interval $[a_a, b_a]$ and zero elsewhere by using algorithm implemented in smart meter such that total energy consumption per appliance resulted from running the program equals to power of appliance multiplied with duration of operation of appliances. Each appliance has min value that is standby mode energy consumption and max value that should not exceed it, or it will damage the appliances.

Resulted ECS ${s_a}^h$ by using CVX program in MATLAB® in Fig. 5 is added with non-shiftable appliances that improves load factor from 0.45 to 0.63 with reduction in electric bill from 136 \$ to 133 \$, as shown in Fig. 6 under usage M = ${s_{u1}}^h$.

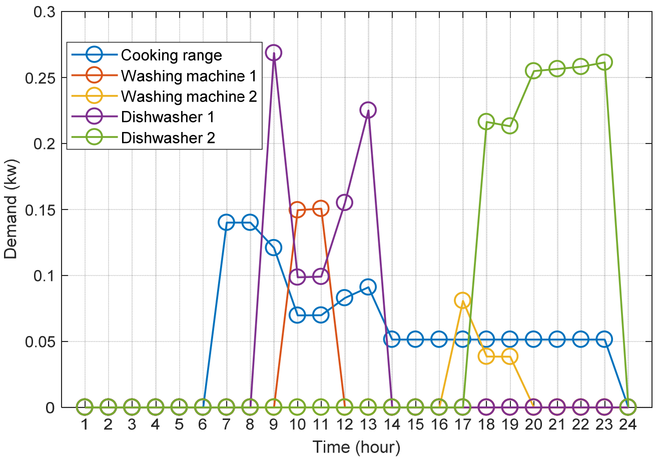

Fig. 5 ECS of shiftable appliances with M = ${s_{u1}}^h$

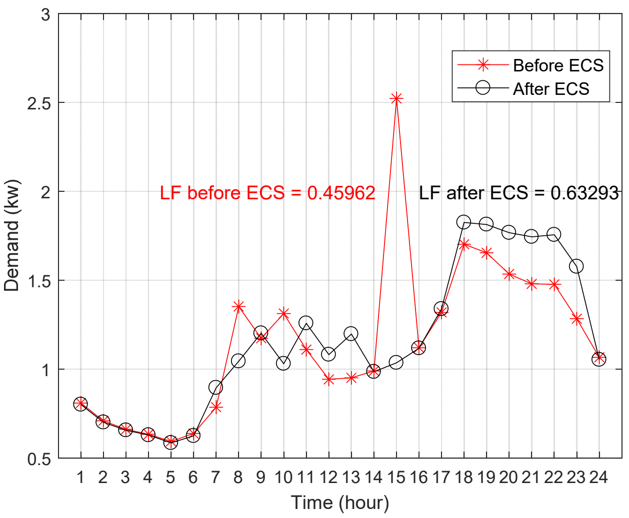

Fig. 6 Total demand of single apartment before and after ECS

If constraint (9) is removed or changed to a constant value for all hours such as 0.7 kWh, the resulted load factor will be 0.56 with reduction in electric bill to be 130 \$. Although the electric bill is further reduced, utility's load factor is not improved compared to the previous case that used ${s_{u1}}^h$. So, the previous case is better to the utility and relatively to customer as well. Figs. 7 and 8 show the effect of using M = 0.7 kWh fixed through all hours on appliances' operation schedule and on total demand in single unit, respectively.

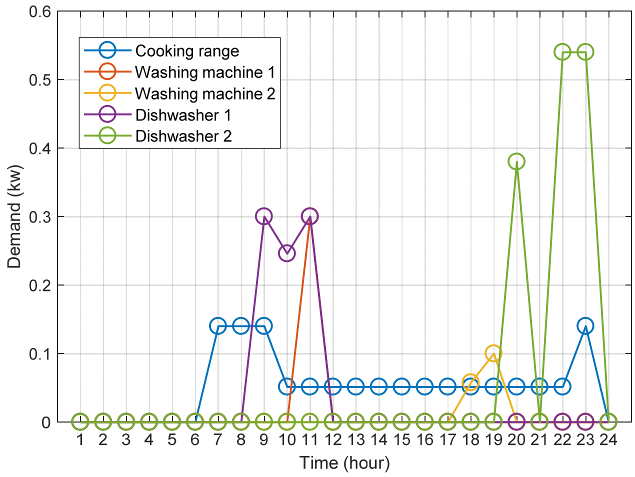

Fig. 7 ECS of shiftable appliances after using M = 0.7 kWh

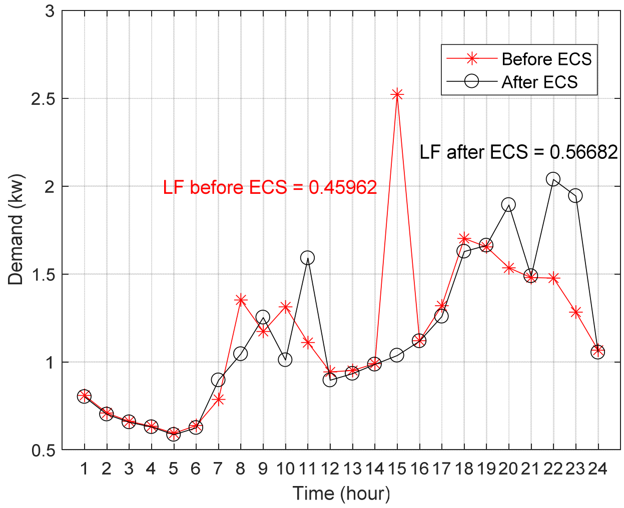

Fig. 8 Total demand in single unit after using M = 0.7 kWh

IV. Load Shifting Method or ECS

Among load management, there is load shifting technique as stated in the previous chapter. It aims to shift load from on peak hours to off peak hours. The method is applied by customer by using iced water instead of hot or using heat storage; however, incentive methods are needed to encourage the customers to shift their loads. Load shifting technique with incentive method is regarded as direct load control form, while ECS shifts load from on peak hours to off peak hours is regarded as indirect load control form [4] by using dynamic pricing. Dynamic pricing is price signals varied every hour, changing operation schedule based on it manually will be difficult and complex. So dynamic pricing is implemented in smart meters that automatically form operating schedule for domestic appliances to achieve optimal total cost, or scheduling preferences, or climate comfort. Although both load shifting from load management and ECS aim for the same purpose, there are distinction between them [11], [15]. These distinctions are epitomized in Table II.

TABLE II
DISTINCTIONS BETWEEN ECS AND LOAD SHIFTING

Point of Distinctions	ECS	Load Shifting
Type of load control	Indirect load control	Direct load control
Dependency on external parties	The consumer shifts their loads without aid of external parties	The consumers shift their loads with aid of external parties
Type of scheme	Dynamic pricing-based program	Incentive based program
Type of information flow	Bi-directional data flow between utility and customer	Unidirectional data flow from utility to customer
Appliances switching	Switching on user's hands	Switching on utility's hands
Duration of operation	Every day phenomena	Used in system emergencies
Customer discomfort	Lesser level	Higher level
Flexibility relation	More flexible to user	More flexible to utility
Equipment required are	Advanced smart meters, sensors	It does not require extra devices
Customer's participation	Requires participation and awareness from customer	It does not need participation and much awareness from customer
System stability	More effective for system stability during everyday event	Effective during some event days
Customer's satisfaction level	Higher	Lower
User's privacy	Less effected	More effected
Cyber attacks	Highly compromised to data theft	Less vulnerable to information theft
System complexity	System is more complex due to priority to different users	System is simple due to main priority is for utility

By using the following mathematical constrained optimal formula to simulate load shifting technique from customer point view [16].

$$\text{Min C} \quad \sum_{u=1}^{U}\sum_{h=1}^{H} P_h^u * t_h * C_h, \tag{10}$$

subject to

$$\sum_{u=1}^{U}\sum_{h=1}^{H} Pnew_h^u * t_h = \sum_{u=1}^{U}\sum_{h=1}^{H} Pold_h^u * t_h \tag{11}$$

$$Pnew_h^u = Pvalue_h^u \quad \forall\ h \in [TK, TH] \tag{12}$$

$$Pvalue_h^u \geq Pnew_h^u \geq Pold_h^u \ \forall\, h \in [To\ , TK], [TH, TD] \tag{13}$$

By simulating the above in CVX program, total power per hour consumed in unit will be limited to value set by utility regardless the desired operating schedule time for appliances. However, the load shifting technique improves load factor from 0.4 to 0.77 with electric bill reduction from 136 $ to 135 $. But, by comparing load shifting method's results with ECS's results, it will appear that, from utility point view, the application of load shifting is better than ECS application since it achieves desired improvement in load factor. While from customer point view applying ECS is much benefitable than load shifting since it reduces total electric bill and it takes into consideration his preferences in scheduling appliances operation. Fig. 9 shows the differences in results from applying both load shifting and ECS.

V. CONCLUSION

Among load management is ECS that shifts appliances' operation schedule per residential unit. But, before applying it, it has been used for whole residential building such that all shiftable appliances for all apartments in single building are gathered and rescheduled all over the day, to estimate max power consumption per hour per apartment. The resulted schedule per apartment is used as limiting value such that shiftable appliances which are rescheduled should not exceed it. So, results show that having smart meter at the entrance of building to estimate max allowed power consumption per hour for total shiftable appliances in apartments is more beneficial than having fixed value set by utility for scheduling domestic appliances in single apartment. The benefits were in load factor improvement and in total reduction in customer's electric bill.

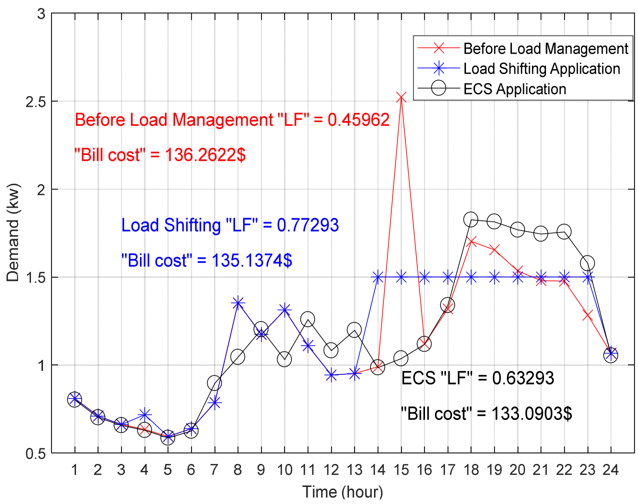

Fig. 9 Effect of applying load shifting and ECS for single unit

ECS is like load shifting technique except it targets customer's satisfaction rather than utility's, and this is achieved by ECS by taking into account resident's preferences in appliances operation schedules. By running both ECS and load shifting programs, from utility point view, load shifting is better than ECS in terms of load factor amelioration and saving the needs of having sensors and smart meters. However, from customer point view, ECS is the best choice since it reduces his/her electric bill and keeps the operation of his/her appliances in the selected time interval set by him/her.

ECS improves utility load factor, although it is not as same as the improvement done by load shifting. So, ECS is considered the most reasonable and achievable technique for both customer and utility's goals.

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