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Energy Scheduling of Smart Appliances at Home under the Effect of Dynamic Pricing Schemes and Small Renewable Energy Source

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Abstract:
With the advancement of smart grid technology, the consumers get the opportunity to participate in various demand response (DR) programs. They can reduce their electricity bill by participating in DR programs. Along with the consumers, the power utility companies also get benefits due to the reduction in high energy peaks on the demand curve. In this paper, we propose an energy scheduling model for the scheduling of smart appliances at home. For the scheduling of appliances, two different dynamic pricing schemes are selected, i) time of use scheme, ii) real time pricing scheme. Along with this, a small renewable energy source in form of rooftop photovoltaic panels is also included to analyse its effect on energy scheduling solution. Finally, the scheduling problem is solved by mixed integer linear programming (MILP) technique. The CPLEX solver of GAMS software is used to apply MILP technique. A case study by considering different cases is done to analyse the effectiveness of formulated model and selected solution approach for the scheduling of the appliances. The simulation results by considering both the pricing schemes have been achieved and compared to get the better idea of the pricing schemes on the energy scheduling results.

Keywords: energy scheduling, demand response, pricing schemes, solar energy, smart grid

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1 Introduction

Smart grid technology is an advance technology having the features which help in the direct involvement of electricity consumers in the grid. The control of the demand is called demand side management. Demand side management comprises three main parts 1) demand response (DR), 2) energy efficiency improvement, 3) energy conservation programs [1–4]. The main aim of different type of DR programs is to encourage the energy users to participate in the electricity market. By participating, the users are incentivised by the utility or they receive benefits in terms of lower electricity bills by scheduling their appliances during low price period [5]. By doing this, the peaks on the energy demand curve also reduce to some lower value, which gives benefit to the utility company [6].

Various methods for the implementation of DR programs in the smart grid have been found in the literature. In some papers, game theory has been used as a solution tool for the problems. To maximize the profit of the utility and satisfaction of the user a Stackelberg game has been established between the utility and the user in [7]. In this paper, authors focused on the planning level energy scheduling problem. They did not include hourly or daily energy scheduling of the consumers. The energy consumption cost of the appliances has been reduced by the game theory based optimization model in [8]. A game has been established among the users to schedule the appliance in such a way that the peak load could be minimized and the energy consumption cost could be reduced. Energy scheduling has been done using real time pricing (RTP) scheme only. Different types of appliances and their load characteristics have not been considered in this paper, which could have significant effect on the results. For the selection of different electrical sources, such as renewable energy sources, fossil fuel sources, a game has been established using game theory in [9]. This helped in the reduction of electricity cost of the users by the scheduling of utility companies. They did not focus on in-home appliances for energy scheduling. Along with the discussed research gaps, in game theory based approaches, the difficulty level of the problems increases with the increase of variables and in the energy scheduling problems, sometimes variables may be in large number. Besides this, game theory approaches sometimes deviate from

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the actual situations. These are few limitations of game theory. Some other methods have also been used for energy scheduling. In [10], social welfare has been maximised using Vickrey-Clarke-Groves method. Authors did not work for peak load shaping at low price time of the electricity, which should be considered to maintain a proper peak to average ratio (PAR). In [11], the scheduling of home appliances has been done using backtracking based scheme. By scheduling the appliances using this method, reduction in the energy peaks has been noticed. This method schedules the appliances according to the task profile and energy consumption profile of the appliances. In [12], an energy scheduling model has been formed to minimise the PAR and to reduce the delay time for using the appliances, which in response satisfies the user. In [11, 12], authors did not include the appliances with interruptible and uninterruptible characteristics, which could give more realistic solution of the appliance scheduling problem. In [13], the authors presented a model for the task scheduling of the home appliances under dynamic pricing conditions. In this paper, authors considered multiple homes-for the energy scheduling and the appliances with only ON-OFF states have been used. They did not consider power scheduling appliances in their literature, which can change the results significantly. A simple linear programming based model has been formed in [14] for the reduction of total energy consumption cost of a home having four appliances. Scheduling has been done using time-of-use (TOU) pricing scheme. Consideration of RTP scheme and more number of appliances could give more actual results. Authors, in [15], solved a convex problem using CVX solver. They formed a two objective energy scheduling problem by considering scheduled based appliances at home. After solving the problem, cost of energy consumption has been minimized and utilization of the appliances has been maximized. Their model did not use any constraint for peak load shaping during the time of low electricity price. Hence, it has been found that in major number of the papers on energy scheduling, many general and frequently used home appliances have not been considered and generally one pricing scheme has been used during energy scheduling, which affect the energy scheduling results at a high extent.

A smart scheduler or controller plays an important role in the scheduling of the home appliances. A master energy controller has been used in [16] for the smart management of the energy with the interaction of the utility company and the consumers. Authors did not explore the characteristics of the appliances for the energy scheduling. For the optimization of the appliances of the consumers, a building energy management controller, for the scheduling of thermal loads, was discussed in [17]. Many authors have considered only flexible appliances [18, 19] or only non-flexible appliances [20, 21] during the formation of scheduling problems. This type of selection of the appliances in energy scheduling problems always leads to a limitation on the scheduling results. Along with this, most of the researchers have focused on the energy scheduling of a single user. Due to this, there is always a scope of energy scheduling for multiple users with modified constraints.

In this paper, the shortcomings of the various papers available for the energy scheduling of the home appliances are considered. For the easy involvement of the users, a central energy scheduler (CES) is proposed for multiple households, having different type of appliances. Appliances have been categorised on the basis of their work application. For the complete user satisfaction, user's preferences for using different appliances are considered in this paper. It is assumed that each user is equipped with a rooftop photovoltaic (PV) panel to consider the solar energy during energy scheduling. The problem is formulated by considering TOU and RTP schemes. The solution is proposed using mixed integer linear programming (MILP). Major contributions of our paper are as follows.

1. In most of the related literature, limited numbers of appliances have been considered for scheduling, which impose a limit on the accurate solution. While, in this work, nearly all frequently used appliances at home are considered.
2. Generally, in most of the related papers, home appliances have been divided into two categories, i) interruptible appliances, ii) uninterruptible appliances. In this paper, the appliances are divided into four categories so that each type of appliance could be fit in any one of the categories.
3. In the related papers, mostly one type of pricing scheme has been used for the energy scheduling. In this paper, the appliances are scheduled under both TOU and RTP schemes. By doing this, comparative analysis of the results achieved by both the pricing schemes, becomes easier.
4. The problem is solved using MILP technique. The main advantage of MILP technique over the other solution tools is that this technique promises a global optimum solution. Along with this, the modifications in this approach are very easy due to its modular structure.
5. Finally, four different cases are considered in the case study and analyse the impact of TOU and RTP schemes on energy scheduling of the appliances in all the cases and successfully plot the energy scheduling results.

The remaining paper is organised as follows: System model is discussed in Section 2 in detail. Different type of appliances and different pricing schemes used in the paper are also discussed in this section. The objective function and the proposed solution are included in Section 3. Case study and the simulation results are presented and discussed in Section 4. Concluding remarks are included in Section 5.

2 Energy scheduling in multiple household scenario

2.1 System model

A set of N neighbourhood households, each having set A of controllable electric appliances has been considered. Appliances of these households are scheduled by CES. It is assumed that the scheduling interval is one day and is divided into 24-small intervals, each of 1-hour duration. Let, H is the set of hourly time intervals, i. e. $H = \{1,2.........H\}$. The CES find out the energy consumption schedule of each appliance of each household at each time interval. For each appliance $a \in A$ of each user $n \in N$, we denote the energy consumption scheduling vector $Z_{n,a}$ as

$$Z_{n,a} \triangleq [Z_{n,a}^{1}, Z_{n,a}^{2} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots Z_{n,a}^{H}] \tag{1}$$

where $Z_{n,a}^{h}$ shows the energy consumption of appliance $a \in A$ of user $n \in N$ at hourly time interval h H. Further, let us assume $E_{n,a}$ is the total energy required for the completion of operation of appliance $'a'$ of the user $'n'$. Hence,

$$\sum_{h \in H} Z_{n,a}^{h} = E_{n,a} \forall n \in N, \forall a \in A \tag{2}$$

Any appliance $a \in A$ of user $n \in N$ can have different energy requirement for the completion of the task. The energy requirement of an appliance depends on its operational characteristics and the way in which it is used. For example, a clothes dryer consumes total 5.5 kWh energy to complete its task in one hour, similarly a personal computer consumes 0.4 kWh energy to complete its task in 4-hours [22]. Different appliances have different operational characteristics. In this paper, the home appliances have been divided in following categories:

– *Type-1:* In this category, we include the interruptible appliances. These appliances can run anytime in user's preferred duration. These can operate only in ON or OFF status. In ON condition, these consume a fixed energy level of $Y_{n,a}^{max}$ and in OFF condition energy consumption level remain $Y_{n,a}^{min}$. Hence, energy consumption of these appliances is formulated as

$$Z_{n,a}^{h} = y_{h,n,,a} Y_{n,a}^{max} + (1 - y_{h,n,a}) \; Y_{n,a}^{min} \forall n \in N, \forall h \in H \tag{3}$$

where $y_{h,n,a}$ is a binary variable, which decides the ON/OFF time of an appliance. To complete the assigned work, the appliance is required to be ON for a certain period. This can be achieved by

$$\sum_{h \in H} (y_{h,n,a} * S_{a,h}) = k_{n,a} \forall n \in N \tag{4}$$

where $S_{a,h}$ is a binary variable, used to select the ON/OFF duration of appliance $a \in A$ on complete time horizon H according to user preferences (if $S_{a,h} = 1$ then ON duration is selected, otherwise OFF duration is selected) and $k_{n,a}$ denotes the total number of slots for interruptible appliance to complete its work. Value of $k_{n,a}$ should be less than or equal to the complete ON duration of appliance $'a'$.

– *Type-2:* In this category, we include the uninterruptible appliances. Uninterruptible appliances may be of two types, 1) with constant load profile, 2) with the variable load profile. After starting, these appliances stop only if the assigned work for them get completed. For the modelling of these appliances we define a binary variable $'x'$ such that,

$$\sum_{m \in M} x_{m,n,a} = 1 \; \forall \; n \in N \tag{5}$$

where $m = 1,2.......M$. Here M, is the total number of possible schedules of appliance $'a'$ in the user preferred duration on the complete time horizon H. Hence, M = (Total user preferred duration – total ON time of appliance + 2). So, energy consumption of these appliances is given by,

$$Z^h_{n,a} = \sum_{m \in M} (x_{m,n,a} * E_{m,h}) \forall n \in N, \forall h \in H \tag{6}$$

where $E_{m,h}$ is the energy consumed in hour $'h'$ of the schedule $'m'$.

– *Type-3:* In this category, we include those interruptible appliances for which users only concern, whether the assigned work can be completed within a certain duration (user preferred duration). Following continues constraint is used for this type of appliances,

$$0 \leq (Z^h_{n,a} * S_{a,h}) \leq E_{n,a} \forall S_{a,h} \tag{7}$$

– *Type-4:* In this category, we include must run appliances such as refrigerator, lighting, etc. These appliances are required to keep ON for a certain duration. The following constraint is used for this type of appliances,

$$Z^h_{n,a} * S_{a,h} = E_{n,a} \forall S_{a,h} \tag{8}$$

Apart from above details, all appliances have some maximum and minimum energy levels indicated by $Y^{max}_{n,a}$ and $Y^{min}_{n,a}$ respectively for each $a \in A$ and $n \in N$. Hence, for the proper energy scheduling vector, the following maximum and minimum energy bound constraint is required,

$$Y^{min}_{n,a} \leq (Z^h_{n,a} * S_{a,h}) \leq Y^{max}_{n,a} \forall S_{a,h} \tag{9}$$

One more important point is that the users can consume a certain amount of energy at each hour. This limit of energy is put by utility and it is indicated by E^{max}. In the energy scheduling problem this is shown by following constraint,

$$\sum_{n \in N} \sum_{a \in A} Z^h_{n,a} \leq E^{max} \forall h \in H \tag{10}$$

2.2 Pricing schemes

Pricing schemes are fixed by the utility for its consumers. In general, there are two types of pricing schemes, 1) static pricing scheme 2) dynamic pricing scheme. In static pricing scheme, generally the price of electricity remains same within the complete energy planning horizon. On the other side, in the dynamic pricing scheme, the price of electricity changes frequently, according to the electricity market conditions [23]. TOU pricing scheme and RTP scheme are two pricing schemes under dynamic pricing category.

– *Time-of-use pricing scheme:* The TOU rates are commonly used time-varying rates. In this scheme a complete day is divided into 2 to 5 intervals and different price is fixed for each interval, depending on the predicted consumer demand in the different time intervals. These rates are generally defined monthly and they remain same in a particular interval of the day throughout the month. These rates greatly affect the scheduling time of different appliances. In general, consumer behavior is to operate their appliances in low rate intervals to decrease their monthly electricity bill. The TOU rates used in this paper are: 11.5 cents/kWh, 9.2 cents/kWh and 5.5 cents/kWh [24].

– *Real time pricing scheme:* In this pricing scheme, generally the price of electricity changes after every hour based on the real-time status of the electricity market. This pricing scheme is difficult to handle because it requires a big amount of data exchange in very short time intervals. But if the needs for the implementation of RTP scheme are fulfilled, then large number of benefits can be achieved. With this scheme, both utilities and consumers get the benefits. RTP scheme increases the efficiency of electricity use and helps the utility to generate higher revenue. The consumers also get the chance to reduce their monthly electricity bill by properly scheduling their appliances under RTP scheme. RTP rates used in this paper are taken from [25].

In the system model explained in the paper, above two pricing schemes have been used for the energy scheduling purpose. The energy scheduler assigns the load according to user preferences and the price of electricity at any time, so that overall electricity cost can be minimized.

3 Objective function and proposed solution

The main objective of this research work is to design an electric energy scheduler, which can schedule the energy consuming appliances in such a way that the consumer can get the most savings on their electricity bill, keeping in view that the impact on user's preferences should be as minimum as possible. For this, the objective function defining the problem is given by the following equation subject to constraints (2) to (10).

$$\mathrm{Q} = \text{minimize} \sum_{h\in H}\sum_{n\in N}\sum_{a\in A}(Z_{n,a}^{h} * P_h) \tag{11}$$

where Q is the total electricity cost of N consumers on time horizon H and P_h is the electricity price at the h^{th} hour of the day. All equality and inequality constraints have been represented by the eqs (2)–(10). In the constraints, $S_{a,h}$ and $x_{m,n,a}$ are auxiliary binary decision variables. Variable $S_{a,h}$ decides the ON and OFF duration of appliance $'a'$ on full time horizon H according to user preferences and the variable $x_{m,n,a}$ is used to select the best schedule for any uninterruptible appliance $'a'$ in its full ON duration on complete time horizon H.

3.1 Inclusion of renewable energy source

In the scheduling of appliances, a small distributed renewable energy sources has been also considered in form of rooftop PV panels. The capacity of rooftop PV panel may be different for each user, depending on the number of installed PV panels. In this work, it has been assumed that PV panels of 3kW capacity have been installed on rooftop of each consumer. Hence, every consumer is having two supply sources at a time. One is supply from the grid and the other is supply from PV panel. If at any time of the day, renewable energy generated by PV panels is higher than the consumer demand at that time, then the extra renewable power can be fed back to the grid, which again gives benefit to the consumer by further reducing their electricity bill. If the energy generated by PV panels is less than the consumer demand at any time, then the remaining electricity will be consumed from the grid. It has been assumed that the power generated by the PV panels is fed to the grid with the same tariff, on which the grid power is purchased. With the inclusion of solar energy, the objective function will be modified as follows:

$$\mathrm{Q} = \text{minimize} \sum_{h\in H}\sum_{n\in N}(U_{n}^{h} * P_h) \tag{12}$$

subject to constraints (2) to (10) and

$$U_n^h \geq \sum_{a\in A} Z_{n,a}^h - V_n^h \;\forall\; n \in N, \forall\, h \in H \tag{13}$$

where U_n^h is a variable, which represents the remaining demand of user $'n'$ at hour $'h'$, left after the utilization of energy generated by rooftop PV panels and has to be fulfilled by the grid at price P_h. V_n^h denote the energy generated by the rooftop PV panels of n^{th} user at h^{th} hour

3.2 Proposed solution

The objective functions represented by the eqs (11) and (12) are linear and have non-integer values while the constraints have both continues and binary values. Therefore, the energy scheduling problem can be solved using MILP techniques. In our problem we have divided full time horizon of 24- hours into 24-equal intervals. So, each interval shows 1-hour duration. MATLAB and GAMS software have been used for the modelling of the problem. For the solution of MILP problem, we use CPLEX solver of GAMS software. It takes less than a few seconds to obtain the solution on 64-bit, intel core- i7, 3.40 GHz personal computer.

4 Case study and results

For the case study, we select three users for the energy scheduling of appliances. Each user represents a separate home. The appliance data for the scheduling purpose has been taken from [22]. Appliances data along with their respective types is shown in Table 1. We select 21-most commonly used electric appliances in summer season.

Table 1: Average wattage and usage time per day of electric appliances.

Appliance	Type	Average wattage (kW)	Operating time (hours)	Per day consumed energy (kWh)
PC	1	0.1	4	0.4
TV	1	0.15	6	0.9
Water pump	1	0.75	3	2.25
Vacuum cleaner	1	0.74	2	1.48
Iron box	1	1.1	1	1.1
Dryer	2	5.5	1	5.5
Coffee maker	2	0.35	1	0.35
Range top (S)	2	1.6	1	1.6
Range top (L)	2	2.7	1	2.7
Microwave oven	2	0.8	1	0.8
Toaster	2	1.1	0.5	0.55
Toaster oven	2	1.5	0.5	0.75
Oven cleaner	2	3.5	0.5	1.75
Washing machine	2	0.665	1.5	0.9975
Dish washer	2	1.2	1.5	1.8
Oven	2	3.5	1.5	4.67
PHEV	3	3.3	4	8.2
A.C.	4	1 (1.5 ton)	9	9
Fridge	4	0.145	24	3.48
Light	4	0.16	12	1.92
Fan	4	0.06	15	0.9

For the solution of scheduling problem to minimize the electricity consumption cost of the consumers, following four cases have been considered:

1. Fully flexible appliance at each home
2. Semi flexible appliances at each home
3. Flexible appliances in users specified duration according to their preferences (same duration for similar type of appliance at each home)
4. Flexible appliances in users specified duration according to their preferences (different duration for similar type of appliance at each home)

The cost of electricity of consumers has been calculated for all four cases using TOU and RTP schemes. In case-1, the ultimate aim of users is to minimize the electricity cost as minimum as possible. This can be achieved, if all the appliances are fully flexible on complete time horizon. In this flexible environment, the scheduler tries to schedule the appliances at the time where the price is minimum. In case-2, it is assumed that the users are semi-flexible for the use of their appliances. It means few selected appliances will be scheduled during the day hours (say 6 A.M. to 11 P.M.) and remaining will be scheduled during the night hours. In this case, some boundaries on the time of use of appliances is put by the users according to their preferences. In case-3, all appliances are scheduled according to user's strict preferences. Here users specify that they are flexible or not flexible for using a particular appliance. In this case, it is assumed that the preferred duration for similar appliances of all users is same. This can be clearly seen in Table 2. In case-4, again all appliances are scheduled according to user's strict preferences. But in this case it has been assumed that the preferred duration for similar appliances of all users is different. The duration of all the appliances of the users is shown in Table 2.

Table 2: Users preferred duration for the appliances in case-3 & case-4.

Appliance	Case-3 Preferred Duration All 3 users	Case-4 Preferred Duration User-1	User-2	User-3
PC	8 AM–6 PM	8 AM–6 PM	8 AM–3 PM	1 PM–11 PM
TV	12 PM–10 PM	12 PM–10 PM	8 AM–4 PM	2 PM–10 PM

Water pump	2 PM–8 PM	2 PM–8 PM	10 AM–4 PM	4 PM–10 PM
Vacuum cleaner	9 AM–12 PM/2 PM–5 PM	9 AM–12 PM/2 PM–5 PM	7 AM–10 AM/1 PM–4 PM	10 AM–1 PM/4 PM–7 PM
Iron box	7 PM–12 AM	7 PM–12 AM	2 PM–7 PM	3 PM–7 PM
Dryer	12 PM–4 PM	12 PM–4 PM	10 AM–2 PM	4 PM–8 PM
Coffee maker	6 AM–8 AM	6 AM–8 AM	7 AM–10 AM	8 AM–10 AM
Range top (S)	9 AM–12 PM	9 AM–12 PM	10 AM–1 PM	11 AM–2 PM
Range top (L)	9 AM–12 PM	9 AM–12 PM	10 AM–1 PM	11 AM–2 PM
Microwave oven	5 PM–8 PM	5 PM–8 PM	7 PM–10 PM	8 PM–11 PM
Toaster	6 AM–8 AM	6 AM–8 AM	7 AM–9 AM	8 AM–10 AM
Toaster oven	5 PM–8 PM	5 PM–8 PM	7 PM–10 PM	8 PM–11 PM
Oven cleaner	12 PM–4 PM	12 PM–4 PM	2 PM–6 PM	3 PM–7 PM
Washing machine	8 AM–12 PM	8 AM–12 PM	6 AM–10 AM	12 PM–4 PM
Dish washer	7 PM–12 AM	7 PM–12 AM	7 PM- 12 AM	8 PM- 1 AM
Oven	9 AM–12 PM	9 AM–12 PM	10 AM–1 PM	11 AM–2 PM
PHEV	8 PM–8 AM	8 PM–8 AM	10 PM–7 AM	12 AM–8 AM
A.C.	12 PM–4 PM & 10 PM–3 AM	12 PM–4 PM & 10 PM–3 AM	12 PM–4 PM & 10 PM–3 AM	12 PM–4 PM & 10 PM–3 AM
Fridge	Full 24 hours horizon	Full 24 hours horizon	Full 24 hours horizon	Full 24 hours horizon
Light	5 AM–10 AM & 5 PM–12 AM	5 AM–10 AM & 5 PM–12 AM	5 AM–10 AM & 5 PM–12 AM	5 AM–10 AM & 5 PM–12 AM
Fan	3 AM–12 PM & 4 PM–10 PM	3 AM–12 PM & 4 PM–10 PM	3 AM–12 PM & 4 PM–10 PM	3 AM–12 PM & 4 PM–10 PM

Figure 1 and Figure 2 show the results of all four cases with TOU and RTP schemes, respectively. In each figure, the total energy demand of three users is shown for all cases. In case-1, we have assumed fully flexible appliances, so all the appliances are scheduled towards the hours where energy price is minimum with the condition that total energy consumed in an hour should be less than or equal to E^{max}. In this paper, it has assumed that E^{max}=15 kWh, combined for all three users. The cost of energy in this case is minimum due to maximum flexibility available for the use of appliances. In case-2 appliances are semi-flexible, so they are scheduled towards the hours of minimum energy price but within the users specified preference hours. The cost of electricity in this case is higher than the cost of electricity of case-1, due to the inclusion of user's semi-flexible preferences. In case-3 and case-4, users have their strict preferred duration for the use of appliances. Results of these two cases show that the scheduling of appliances is done in those hours where users have shown their interest to use them. So during the user's preferred duration, minimum energy price is selected for the scheduling so that the objective of minimization of total electricity cost can be achieved. Compare to case-1 and case-2, cost of electricity in case-3 and case-4 is higher, which shows the effect of inclusion of users preferences.

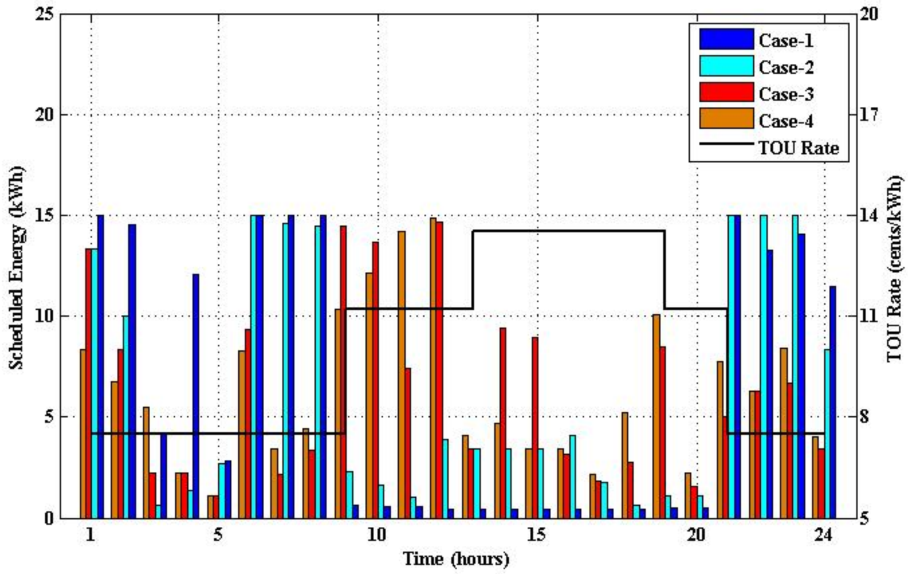

Figure 1: Scheduled energy with TOU scheme and without considering solar energy.

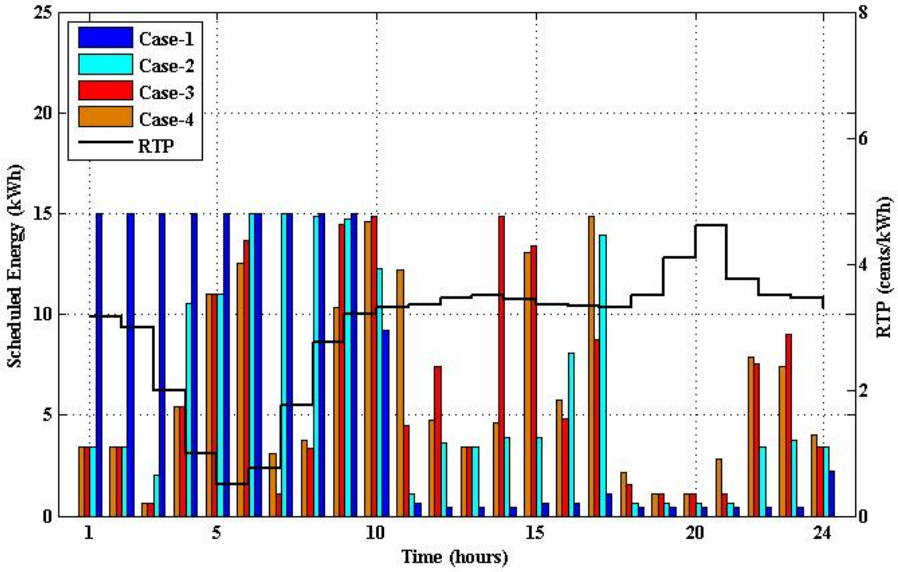

Figure 2: Scheduled energy with RTP scheme and without considering solar energy.

Further, all four cases have been analysed by considering solar energy generated by rooftop PV panels, installed at the user's home. Again, the same TOU and RTP schemes have been used for the analysis. Energy scheduling results have been shown in Figure 3–Figure 6. Figure 3 and Figure 4 show the results of energy scheduling in all four cases with the condition that extra solar energy in an hour, which is left after the scheduling of all appliances, is not fed to the grid. On the other hand, Figure 5 and Figure 6 show the results of energy scheduling in all four cases with the condition that extra solar energy in an hour, which is left after the scheduling of all appliances, is fed to the grid. This can be clearly seen in the result figures that the scheduled energy peaks have been reduced due to the use of solar energy. Similar to the previous analysis (i. e. without considering solar energy), in this case also, the scheduling of appliances is done towards the hours where energy price is minimum and user's preferences are fulfilled. With the use of solar energy, cost of electricity is drastically reduced in all cases as compared to the cases without solar energy.

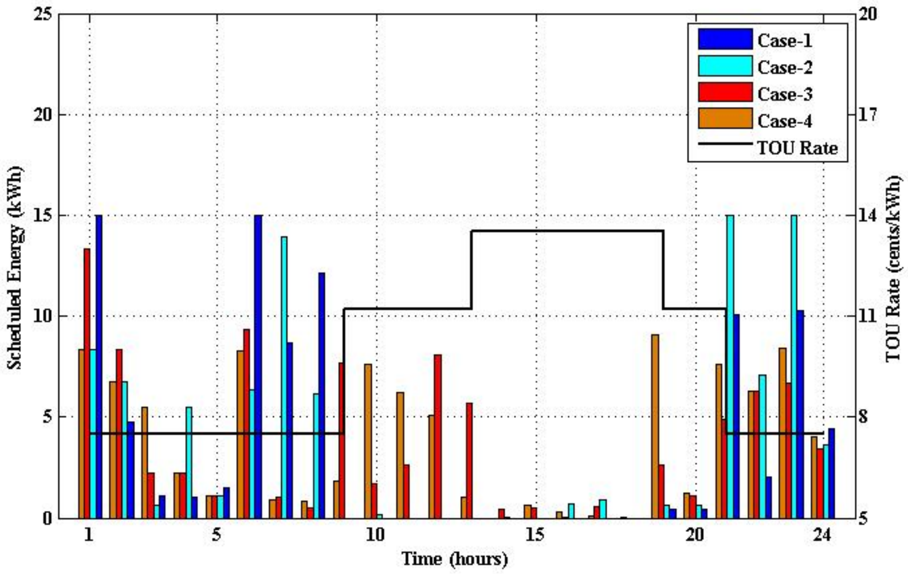

Figure 3: Scheduled energy with TOU scheme and solar energy.

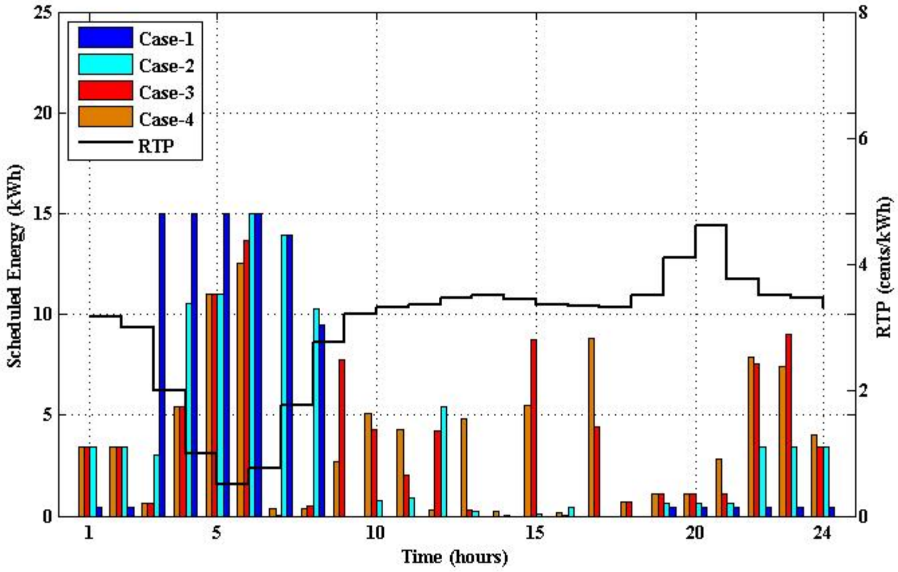

Figure 4: Scheduled energy with RTP scheme and solar energy.

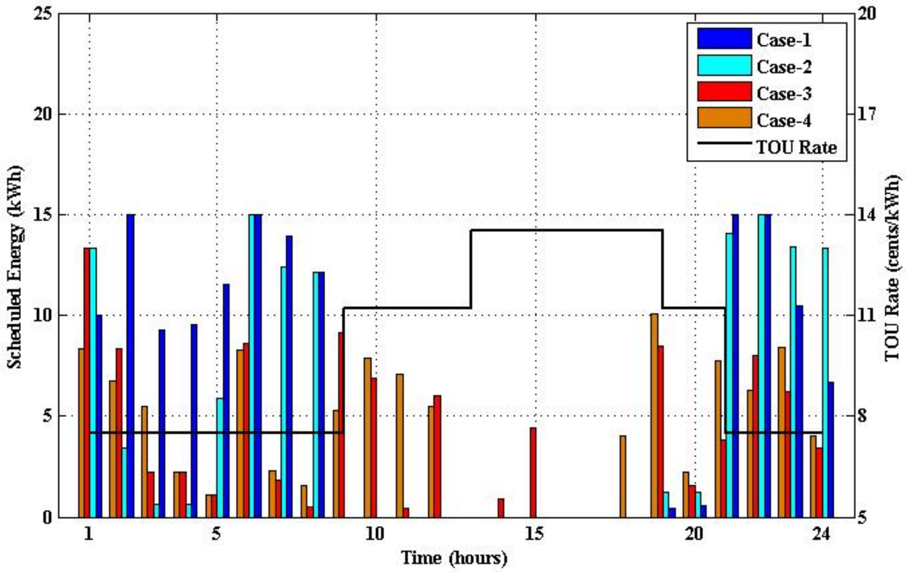

Figure 5: Scheduled energy with TOU scheme and selling extra solar energy to grid.

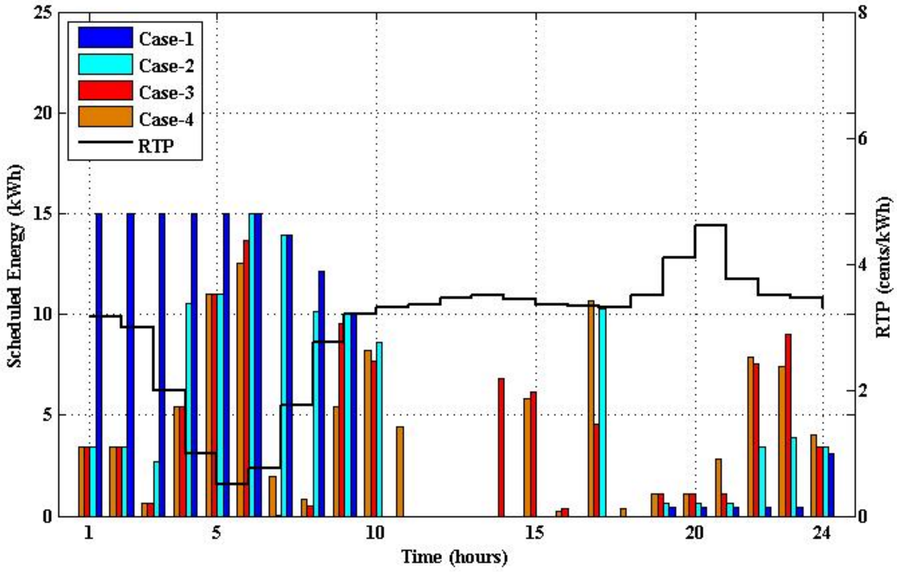

Figure 6: Scheduled energy with RTP scheme and selling extra solar energy to grid.

Table 3 and Table 4 shows the total energy demand of three users on the grid and total energy cost of these users in all four cases, with and without considering solar energy. From the tables, it can be seen that the electricity price is minimum in case-1 i. e. when users are fully flexible to use any appliance at any time on complete horizon. The electricity cost is highest in case-3 and case-4 i. e. when all appliances are scheduled according to user's strict preferences. It can be seen in Table 3 that with TOU scheme, in case-3 and case-4 the user's have to pay 29.97 % and 28.49 % more price respectively for scheduling the appliances, in comparison to case-1. This extra payment is made to meet the user's preference. Similarly the extra payment with RTP scheme is 22.63 % and 22.52 % for scheduling of appliances as case-3 and case-4 respectively. In Table 4, with TOU scheme, compare to case-1 the extra cost for the inclusion of user's preferences is 23.44 % and 24.86 %, when extra solar energy is not fed to the grid and is 65.89 % and 63.98 %, when extra solar energy is fed to the grid, for scheduling the appliances according to case-3 and case-4 respectively. This high increment in payment for scheduling the appliances as case-3 and case-4, with the condition that extra solar energy is fed to the grid, shows that the flexible use of appliances in such conditions can save huge amount of money. Similarly the extra payment with RTP scheme is 47.01 % and 46.13 %, when extra solar energy is not fed to the grid and is 46.33 % and 46.18 %, when extra solar energy is fed to the grid, for scheduling the appliances according to case-3 and case-4 respectively. The cost of electricity mentioned in Table 4 is lower than the cost of electricity mentioned in Table 3, due to reduced demand on the grid because of the inclusion of locally generated solar energy. Case-2 in the tables shows the results for the scheduling of semi-flexible appliances and the cost of electricity in this case lie in between case-1 and case-3. From the comparative analysis, it is clear that the user's benefit is highest in case-1 and his satisfaction is highest in case-3 and case-4. This analysis can help the utilities to offer different scheduling options to their customers and the customers can also select the best schedule which can fulfil their needs with minimum electricity cost.

Table 3: Total energy demand and total energy cost of the users in all four cases without considering solar energy.

	With TOU scheme			
	Case-1	**Case-2**	**Case-3**	**Case-4**
Total energy demand on grid	153.2925	153.2925	153.2925	153.2925
Total Electricity Cost (TEC) in cents	870.42	985.01	1242.91	1217.21
	With RTP scheme			
	Case-1	**Case-2**	**Case-3**	**Case-4**
Total energy demand on Grid	153.2925	153.2925	153.2925	153.2925
Total Electricity Cost (TEC) in cents	333.50	380.71	431.03	430.45

Table 4: Total energy demand and total energy cost of the users in all four cases with considering solar energy.

	With PV & TOU scheme							
	Case-1		Case-2		Case-3		Case-4	
Solar energy back to grid	**No**	**Yes**	**No**	**Yes**	**No**	**Yes**	**No**	**Yes**
Total energy demand on grid	86.90	86.90	92.46	86.90	90.43	86.90	93.35	86.90
Total Electricity Cost (TEC) in cents	481.17	193.38	523.73	308.54	628.52	566.89	640.41	536.82
	With PV & RTP scheme							
	Case-1		**Case-2**		**Case-3**		**Case-4**	
Solar energy back to grid	**No**	**Yes**	**No**	**Yes**	**No**	**Yes**	**No**	**Yes**
Total energy demand on grid	86.90	86.90	90.62	86.90	93.92	86.90	93.94	86.90
Total Electricity Cost (TEC) in cents	126.81	112.98	176.81	160.86	235.38	210.51	239.32	209.94

5 Conclusion

The work in this paper is done to achieve the main aim of smart grid technology, which is, to give benefits to both the electricity consumers and to the power utility. In the propsed energy scheduling model, we have focused on multiple households together, for their easy involvement in the smart grid to reduce their electricity consumption cost. The common energy scheduler used for the energy scheduling of multiple users, communicate with the smart meters of the consumers to exchange various information like energy demand, price signals etc. between the consumers and the power utility. To achieve the user's satisfaction, users have declared their preferences for using different type of appliances. Two pricing schemes, TOU and RTP, have been used in the paper. The price data are real data, taken from the power companies for scheduling purpose. The impact of two pricing schemes has been monitored using energy scheduling results, which have been explained in Table 3 and Table 4, in detail.

A case study with different cases has been done to verify the effectiveness of the proposed model and MILP based solution technique. Finally, the formulated mixed integer linear programming problem has been solved by considering small distributed energy source in the form of rooftop PV panels and satisfactory results have been achieved. It can be seen from the simulation results that the energy peaks have been shifted towards the lower price time, which has significantly reduced the electricity consumption cost along with the satisfaction of the consumers. High energy peaks, at low price time, have been stopped by putting an energy limit on per hour energy consumption, which helped in maintaining a good PAR value. In future, this work can be further extended for the energy scheduling of commercial and industrial appliances and new RTP schemes can also be used.

Nomenclature

Parameters

N Set of households (users)

A Set of appliances at each home

H Scheduling planning horizon (in hours)

$Z^h_{n,a}$ Energy (kWh) consumption of appliance a of user n at hourly time interval h.

$E_{n,a}$ Total energy required (kWh) for the completion of operation of appliance a of the user n

$Y^{max}_{n,a}$ Maximum energy (kWh) consumed by an appliance a of user n in an hour

$Y^{min}_{n,a}$ Minimum energy (kWh) consumed by an appliance a of user n in an hour

$S_{a,h}$ Binary variable to select the ON/OFF duration of appliance a on complete time horizon H

$y_{h,n,a}$ Binary variable to decide the ON/OFF hour of an appliance a of type-1 of user n

$k_{n,a}$ Total number of slots for interruptible appliance a of user n to complete its work

M Total number of possible schedules for appliance a of type-2

$x_{m,n,a}$ Binary variable to select a schedule m for appliance a of user n

$E_{m,h}$ Energy (kWh) consumed in hour h of the schedule m.

E^{max} Maximum energy (kWh) allowed to consume in an hour by all users

P_h Electricity price (cents/kWh) at the h^{th} hour of the day

Q Total electricity cost (cents) of N consumers on time horizon H

V_n^h Energy generated by the rooftop PV panels of n^{th} consumer at h^{th} hour

U_n^h Energy demand (kWh) of user n at hour h, which left after the utilization of energy generated by rooftop PV panels

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