Residential Energy Consumption Scheduling Techniques Under Smart Grid Environment

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Abstract. In recent years the load demand by residential consumers are rapidly increasing due to the usage of many electric appliances in daily needs. Load demand during peak hours is becoming increasingly larger than off-peak hours, which is the major reason for inefficiency in generation capacity. Introduction of smart grid technology in Demand Side Management programs provides an alternative to installation of new generation units. Consumers can play a major role in reducing their energy consumption by communicating with utilities so that they can minimize their energy costs and get incentives, which also helps utilities in many ways. Smart grid technologies provide opportunities to employ different pricing schemes which also help in increasing the efficiency of appliance scheduling techniques. Optimal energy consumption scheduling reduces the peak load demand in peak hour. Peak average ratio (PAR) also minimizes the energy consumption cost. In this paper, we observes different energy consumption scheduling techniques that schedule the house hold appliances in real-time to achieve minimum energy consumption cost and to reduce peak load demand in peak hours to shape the peak load demand. Formulation and Solution methodology of residential energy consumption scheduling is presented with simulation results illustrating the working of the model.

Keywords: Smart grid · Demand side management · Energy consumption scheduling · Peak load demand · Energy pricing

1 Introduction

In recent years energy demand by the residential consumers are rapidly increasing due to the usage of many electrical appliances, the utilities are unable to satisfy users requirement because of this, there is power shortage in every place. Especially in small towns in India there is 6-8 h power cut daily during peak hours, due to this the efficiency of power utilization is decreasing. Utilities facing many problems, so there is huge need for the installation of new power generation units which needs lot of investment though it cannot solve the problem which is to increase efficiency. Due to the advancement of smart grid technology in Demand side management programs, it has become an alternative for the installation of new power plants. Demand side management programs are implemented by utilities control energy consumption of the consumers, utilities motivate consumers to participate in DSM programs and they offer incentives [1]. DSM programs provides energy efficiency programs, demand response

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programs, fuel substitution programs, and Residential or commercial load management programs. Residential load management programs consist of mainly 2 objectives reducing consumption and shifting consumption. Utilities motivate people to reduce their power consumption by using smart homes. Energy production costs vary with time according to the generation capacity, but utilities charge average price to the consumers according to their calculation of profits. People consume energy without depending on the time and sometimes there will be huge overlap in the usage of loads and peak load increases drastically, it causes power shortage or increases energy consumption cost. DSM programs helps users to reduce their energy cost by changing their energy consumption patterns or they will get incentives from utilities for reducing or shifting their usage when system reliability is jeopardized.

2 Demand Side Management

Demand side management (DSM) refers to the programs implemented by the utilities to control the energy consumption of the consumers to increase the efficiency in usage of available power without installing new generation plants [1]. Residential DSM programs mainly concentrates on reducing or shifting of energy consumption, utilities motivates users to reduce energy consumption by using energy efficient buildings like smart homes, there is a need to shift the house hold appliances to off peak hours from peak hours to reduce PAR(Peak Average Ratio) which improves the reliability of power system network. Shift-able appliances are two types, namely, (i) Power shift-able loads and (ii) Time shift-able loads. For power shift-able appliances we can vary the energy supply within standby power limits according to the availability of generation, but for Time shift-able appliances we cannot vary the power supply since they will have their own power consumption patterns and we can only shift the time of usage according to the user's preference. Load shifting is becoming very important as the usage of loads with high power requirement is increasing and they will affect demand curve very much, these loads will double the PAR sometimes, so we need to schedule these loads carefully. Demand response is a part of DSM strategies which is defined as "changes in electricity usage by end-use customer's form their normal consumption pattern in response to changes in the price of electricity over time, or to incentive payments designed to induce lower electricity use at times of high wholesale market prices or when system reliability is jeopardized". Figure 1 shows the concept of demand response under smart grid environment. Demand response is not a new word to the world but due to the advancement in Smart grid technology these DR options are becoming very popular because of the participation of the people is increasing. There are different types of DSM strategies some of them are Direct Load Control [3], Real Time pricing [4], Time-of-use pricing, Critical peak pricing, Emergency Demand Response, Interruptible load etc. Since the goal of DSM programs coincides with target of smart grid which is to build a secure, Reliable, economical, clean and efficient power system. If these are combined simultaneously, it is bound to greatly promote the development of power industry.

In further sections we will discuss about energy consumption scheduling techniques for Residential Network with multiple users and one energy source [5, 6].

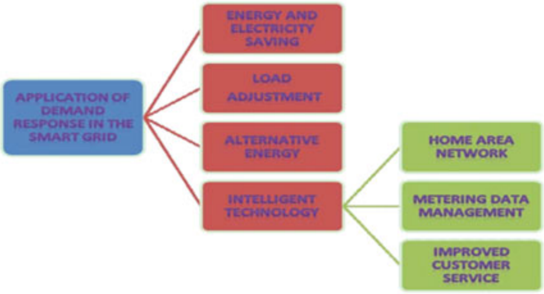

Fig. 1. Demand response under the smart grid environment

Consider a residential network having single energy source and multiple users which is connected to the electric grid. Each user contains ECS (Energy Consumption Scheduler) units in their smart meters which are connected to the power line coming from Energy source. These smart meters are also connected to LAN (Local Area Network) to communicate with utility and between users.

3 Energy Consumption Scheduling of a Residential Network

Consider a residential network having single energy source and multiple users which is connected to the electric grid.

Figure 2 shows a residential network having three appliances. Each user contains ECS (Energy Consumption Scheduler) units in their smart meters which are connected to the power line coming from Energy source. These smart meters are also connected to LAN (Local Area Network) to communicate with utility and between users.

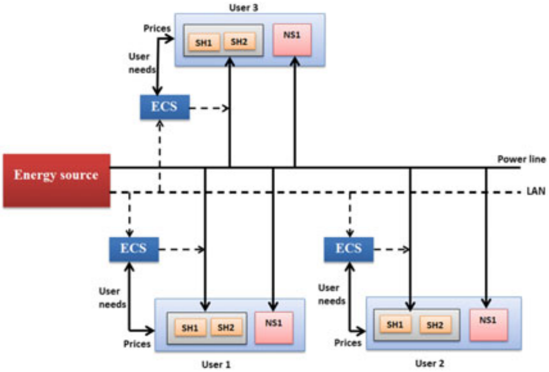

Fig. 2. Energy consumption scheduling model with 3 users each having 3 appliances

In our model we considered 3 users, each having set of appliances differentiated as shift-able and Non-shift-able loads. ECS units can alter only the power supplied to the shift-able loads according to the user needs. Users provide their Energy requirement, time preferences and usage of appliances to the utility through ECS and in return they will provide energy consumption cost. Each user n € ℕ, (ℕ is set of users and the number of users is N) have set of household appliances denoted with A_n. For each appliance $a \in A_n$ we will have an energy consumption scheduling vector

$$X_{n,a} = \left[x_{n,a}^{1}, x_{n,a}^{2}, \cdots x_{n,a}^{H}\right]$$

where H is total no of hours

The aim of ECS units is to get optimal solution for Energy Consumption scheduling vector according to the user's preferences and constraints.

$$PAR = \frac{DailyPeakLoad}{AveragePeakLoad} = \frac{L_{peak}}{L_{avg}}$$

$$PAR = \frac{\max_{h\in H}^{L_h}}{\frac{\sum_{h\in H}^{L_h}}{H}} = \frac{H \max_{h\in H}^{\left(\sum_{n\in N} \sum_{a\in A_n} x_{n,a}^{h}\right)}}{\sum_{n\in N} \sum_{a\in A_n}^{E_{n,a}}} \tag{1}$$

where

$x_{n,a}^{h}$ - Energy consumed by an appliance at an hour

$$l_n^h = \sum_{a\in A_n} x_{n,a}^{h} \tag{2}$$

$$l_h = \sum_{n\in N_n} l_n^h \tag{3}$$

$$L_{peak} = \max_{h\in H} L_h \tag{4}$$

$$L_{avg} = \frac{\sum_{h\in H} L_h}{H} \tag{5}$$

$\mathrm{l}_{\mathrm{n}}^{\mathrm{h}}$ - Total load at hour h
l_n^h- Total load at hour h
l_h- Daily load for user n (for all hours)
L_h- Total load of all users at each hour of the day
L_{peak} - Daily peak load
L_{avg} - Average load
$E_{n,a}$- Predetermined total daily energy consumption

4 Energy Cost Model

In this model users can directly reduce their energy consumption cost so that more people participate and utilities can get benefits from it. Using concept of smart pricing utilities can offer different types of energy cost programs [7, 8]. We considered a simple quadratic cost function which represents actual energy cost as for thermal generators [9]. Let us denote the cost of energy consumption for an hour as $C_h(L_h)$. Energy cost varies to the energy consumed by the user. During peak hours (generally day time) the energy cost will be high compared to off-peak (generally night hours) hours.

Energy cost increases as energy consumption increases

$C_h\left(L_h^1\right) < C_h\left(L_h^2\right)$ for all $L_h^1 < L_h^2$

Energy cost function is

$$C_h\left(L_h\right) = a_h L_h^2 + b_h L_h + c_h \tag{6}$$

where a_h, b_h and $c_h \geq 0$

From (2) to (5)

$$C_h\left(L_h\right) + a_h\left(\sum\nolimits_{n\in N}\sum\nolimits_{a\in A_n} x_{n,a}^h\right)^2 + b_h\left(\sum\nolimits_{n\in N}\sum\nolimits_{a\in A_n} x_{n,a}^h\right) + c_h \tag{7}$$

5 Parameter Minimization

In parameter Optimization, the objective problem is formulated as follows

Objective Function: PAR Minimization

$$\min_{X_n \forall n\in N} \frac{H \max_{h\in H}\left(\sum_{n\in N}\sum_{a\in Ax} x_{n,a}^h\right)}{\sum_{n\in N}\sum_{a\in A} E_{n,a}} \tag{8}$$

Constraints:

$$a_{n,a} < \beta_{n,a} \tag{9}$$

For each appliance user needs to select the starting time $(\alpha_{n,a})$ and ending time $(\beta_{n,a})$ for the operation, Power supply should be between the time interval $(\alpha_{n,a})$ and $(\beta_{n,a})$, starting time of the supply should be less than ending time.

$$\sum\nolimits_{h=a_{n,a}}^{B_{n,a}} x_h^a = E_{n,a} \tag{10}$$

For each user n and appliance a there will be a predetermined energy $(E_{n,a})$ which is given by user, the total daily energy consumption for an appliance between the time interval $(\alpha_{n,a})$ and $(\beta_{n,a})$ should be equal to $(E_{n,a})$.

$$x_{n,a}^h = 0 \tag{11}$$

Energy consumed by an appliance at an hour other than time interval between $(\alpha_{n,a})$ and $(\beta_{n,a})$ is zero.

$$\beta_{n,a} - a_{n,a} \geq 0 \tag{12}$$

Time interval needed to finish the operation

For any appliance the time interval chosen by the user should be greater than the time interval needed to finish the operation

$$\sum\nolimits_{h \in H} L_h = \sum\nolimits_{n \in N} \sum\nolimits_{a \in A_n} E_{n,a} \tag{13}$$

The total energy consumed in all hours should be equal to the energy consumed by all users' appliances

$$\gamma_{n,a}^{\min} \leq x_{n,a}^{h} \leq \gamma_{n,a}^{\max} \tag{14}$$

Energy consumed by an appliance at any hour should be between minimum standby power and maximum standby power. Standby power is a power which is consumed by an appliance in switched off mode or standby mode. In our objective function (8) the denominator (predetermined energy $E_{n,a}$) is fixed for optimization problem, so we can neglect it and optimize the simplified one, so minimization of peak load satisfies the objective

$$\min_{X_n \forall n \in N} \left\{ \max_{h \in H} \left(\sum\nolimits_{n \in N} \sum\nolimits_{a \in A} x_{n,a}^{h} \right) \right\} \tag{15}$$

The above objective function (15) contains two functions (min and max) it is difficult to optimize so it can be further simplified as

$$\min_{X_n \forall n \in N} L$$

Subject to $L \geq \sum\nolimits_{n \in N} \sum\nolimits_{a \in A} x_{n,a}^{h}$

and the above constraints (9) to (14)

Since our objective function and constraints are linear implies it is linear program and it can be solved using simplex method or interior point method. For solving this problem MATLAB optimization tool box has been for linear programming method.

6 Cost Minimization

In cost Optimization, the problem is formulated as following

Objective Function: Energy consumption cost minimization

$$\min_{X_n \forall n \in N} \left\{ \sum_{h=1} C_h \left(\sum\nolimits_{n \in N} \sum\nolimits_{a \in A} x_{n,a}^{h} \right) \right\}$$

Constraints: Eqs. (9) to (14)

Since our objective is convex function it can be solved using convex programming techniques. For solving this problem we have chosen MATLAB optimization tool box [10, 11] which has Quadratic programming method in it.

Case Study -1: We considered 3 users each having 3 appliances model with 2 shift-able and 1 Non-shift-able loads. ECS cannot schedule Non-shift-able appliances; some of them are Heater, Hob, micro oven, Refrigerator, freezer, electric stove and lighting for some standard bulbs etc. Tables 1 and 2 Provide the data for energy consumption before scheduling and users preference accordingly. Shift-able appliances have soft energy consumption scheduling constraints some of them are Water boiler, PHEV, Washing machine, Dish washer, clothes dryer etc. Before participating in any program users consume their energy randomly without scheduling, we took most possible worst case as data.

Table 1. Data for Energy consumption before scheduling

Users	Appliance type	Appliance	Total energy consumption (kWh)	Energy usage at different times (kWh)
User 1	NS	Refrigerator	1.32	1 to 24 -0.055kWh for each hour
	SH	Washing Mc	1.49	9 to 12-0.5kWh for each hour
	SH	PHEV	9.9	10 to 13-3.3 for each hour
User 2	NS	Refrigerator	1.89	1 to 24- 0.079kWh for each hour
	SH	Dish Washer	1.44	10th and 20th hour -0.72kWh
	SH	PHEV	9.9	11 to 14- 3.3 for each hour
User 3	NS	Lighting	1	1 to 24-0.042for each hour
	SH	Washing Mc	1.49	16 to 19 -0.5kWh for each hour
	SH	PHEV	9.9	13 to 16- 3.3 for each hour

Every user should give their predetermined energy, time preference, standby power of appliance, type of appliance whether it is shift-able or Non-shift-able. Data is provided by the users to the utility at the beginning of the day for the schedule of that particular day. For all Non-shift-able appliances 24 h (whole day) given as the time preference, users want these appliances to be ON continuously, standby power is taken as $\left(\frac{\text{predetermined Energy}}{\text{time interval}}\right)$ i.e. user 1's Non-shift-able appliance standby power = $\left(\frac{1.32}{24}\right)$ = 0.055. Standby power for other appliances is taken according to their power usage Time preference and predetermined energy is taken according to the practical data available. In our quadratic cost function (7) we assumed a_h = Rs. 2, b_h = Rs. 0.02 during dynamic hours from 8:00 AM to 12:00. a_h = Rs. 1.8, b_h = Rs. 0.018 during night time from 12:00 to 8:00 AM. It can be observed that Peak load is very high because users consumed their energy randomly and there is huge overlap in the usage of heavy loads. Figures 3 and 4 shows the energy consumption of users

Table 2. Data for scheduling according to user's preference

Users	Appliance type	Appliance	Predetermined energy (kWh)	Time preference	Standby power (kw)
User 1	NS	Refrigerator	1.32	1 to 24	0.055
	SH	Washing Mc	1.49	8 to 12,18to24	0.0005
	SH	PHEV	9.9	1 to 13	
User 2	NS	Refrigerator	1.89	1 to 24	0.07875
	SH	Dish Washer	1.44	10 to 15	
	SH	PHEV	9.9	11 to 24	
User 3	NS	Lighting	1	1 to 24	0.04166
	SH	Washing Mc	1.49	6 to10,16to24	0.0005
	SH	PHEV	9.9	10 to 19	

before and after scheduling along with values of reduces values of peak, average and peak average ratios.

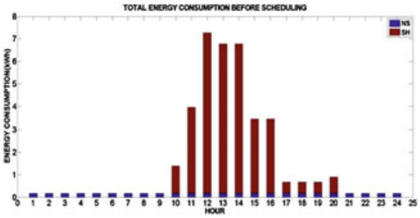

Fig. 3. Energy consumption of users before scheduling Peak = 7.27 Average = 1.59 PAR = 4.55

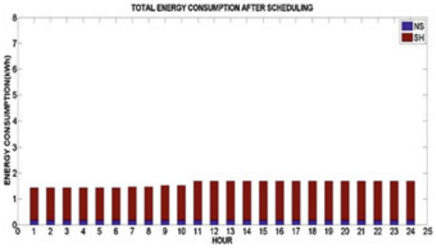

Fig. 4. Energy consumption of users after scheduling Peak = 1.69, Average = 1.59, PAR = 1.06

It can be observed that the energy consumption of users after scheduling, the peak load is reduced to 1.69 and PAR to 1.06, since the usage of heavy load appliances is scheduled without overlapping the peak load and PAR are highly improved. There is no change in the usage of Non shiftable appliances. In our case PHEV is the heavy load which shapes the load curve, it is distributed in the three zones of the day (considering user's preference) so that they won't overlap to decrease the peak load.

Figure 5 shows the Energy schedule consumption between users. In the Energy scheduling of individual users before and after ECS units, it can be observed that there is no change usage of Non shiftable appliances, for every user after scheduling PAR and Peak load is reduced Total energy consumption cost before and after scheduling. Cost is reduced from Rs. 221.59 to Rs. 53.17, we can observe that before scheduling most of the energy consumed in peak hours but after scheduling part of it is shifted to off peak hours.

Figures 6 and 7 shows the Total energy cost before and after scheduling. In the Total Energy consumption before scheduling with cost minimization, it can be observed that the PAR is reduced from 7.27 to 1.966.

Figure 8 shows the Energy consumption after scheduling with cost minimization, where a uniform energy consumption pattern can be observed.

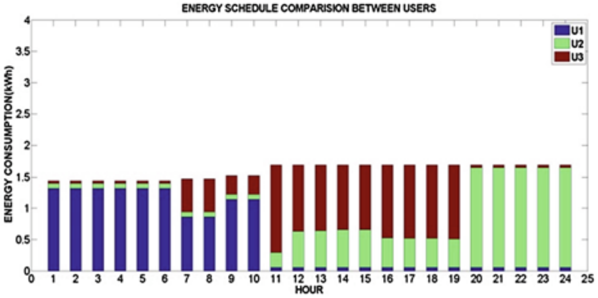

Fig. 5. Energy schedule comparison between users

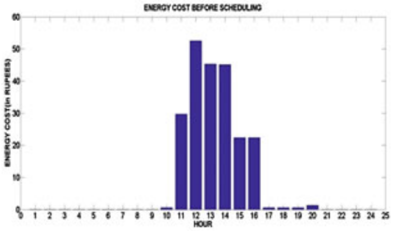

Fig. 6. Total energy cost before scheduling

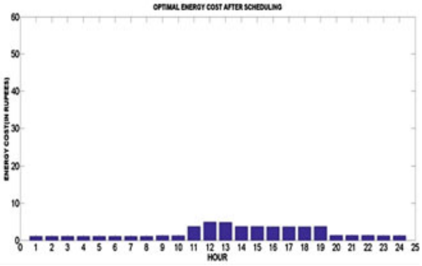

Fig. 7. Optimal energy cost after scheduling

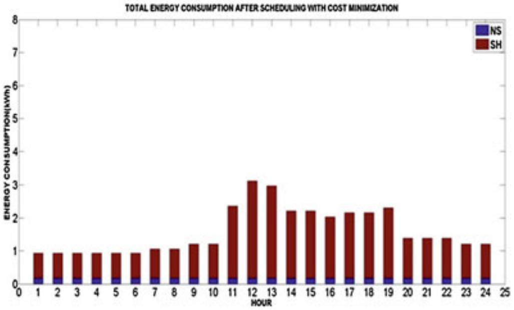

Fig. 8. Energy consumption after scheduling with cost minimization

Table 3 shows the Energy consumption cost before and after scheduling. It can be observed that there is significant reduction in the cost of each user after energy scheduling.

Table 3. Energy consumption cost before and after scheduling.

User	Energy consumption cost	
	Before (Rs)	After (Rs)
1	82.70	14.95
2	70.05	16.15
3	68.64	22.47
Total	**221.59**	**53.17**

Mixed Integer Programming Method was employed for energy consumption scheduling of Residential network. This technique is advancement of previous one which is not suitable for most appliances in practice, so we took single user to develop the model. Here we differentiated Shift-able loads as power shift-able and Time shift-able. For some appliances we cannot change its own power consumption pattern we can only shift its usage from one time to another according to our requirements. For example In previous technique we considered washing machine as power shift-able load and scheduled by reducing the power at different time slots, but in practice we cannot control the power we can only shift the usage of the appliance and after that it will run according to it power consumption pattern. For Time shift-able appliances smart meter (ECS) controls the switch and provide power according to its own consumption schedule during the available time slots considering user's preference. So we considered 3 types of loads in this model.

7 Single User Residential Network Model

Consider a single user connected to the power network for energy supply and also to LAN (Local Area Network) for information exchanges between other users and utility. In the above diagram power will be delivered from power line to the user, in the middle Energy Consumption Scheduler controls Time shift-able and power shift-able according to the user's preference. But cannot schedule or control non-shift-able appliances it only takes requirement from the user. In our proposed technique, the schedule of the energy consumption of user is done by taking Peak Average Ratio minimization as an objective (Fig. 9).

As explained earlier in our first technique we can simplify our objective function by neglecting Average load (since it is constant), so it is enough to minimize Peak load.

8 Problem Formulation for Peak Load Minimization

The problem formulation for peak load minimization cane be written as follows

Minimize of Peak load L

$$\min_{L=x_{a,h}h} L$$

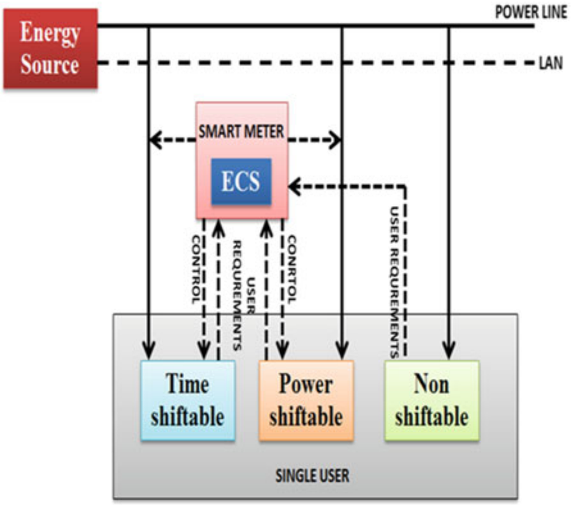

Fig. 9. Energy schedule model for single user in Residential Network

Subject to the Constraints

$$\sum\nolimits_{a \in A} x_{a,h} \leq L, \forall h \in H \tag{16}$$

The total energy consumed by all appliances at an hour should be less than peak load.

$$x_{n,a}^{h} \geq 0 \tag{17}$$

The energy consumed by an appliance at an hour should be non-negative.

$$x_{n,a}^{h} \geq N_a, \forall a \in N, \forall h \in H \tag{18}$$

The energy consumed by every Non-shift-able appliance for an hour should be less than its fixed power requirement per hour (N_a). So the total predetermined energy for a Non-shift-able appliance is calculated as follows, EN,a = (no of working hours) x(N_a), N is set of Non-shift-able appliances.

$$\gamma_{n,a}^{\min} \leq x_{n,a}^{h} \leq \gamma_{n,a}^{\max} \forall a \in P \tag{19}$$

∀ th ∈ during its preferred working hours

Energy consumed by a power shift-able appliance at any hour should be between minimum standby power and maximum standby power. Standby power is a power which is consumed by an appliance in it's switched off mode or standby mode.

P is set of power shift-able appliances.

Table 4. Preferences given by the users for scheduling of their loads for 24 h

Appliance	Type	Hourly consumption (kWh)			Time preference			Energy requirement (kWh)	
		U1	U2	U3	U1	U2	U3	U1	U2
Fridge	NS	0.12	0.12	0.14	24 h	24 h	24 h	2.88	2.88
Heater	NS	1	1	1	9 pm to10 pm 3am to 5am	8 pm to 10 pm 3am to 6am	7 pm to 9 pm 4am to 7am	3	5
Water boiler	PS	0–1.5	0–1.5	0–1.5	24 h	8am to 8 pm	24 h	3	2
PHEV	PS	0.1–3	0.1–3	0.1–3	8pmto 8am	10 pm to8am	10 pm to 8am	5	4
Washing mc	TS	1kWh-1sthr 0.5kWh-2nd hr	1kWh -1sthr 0.7kWh-2nd hr	1.2kWh-1st hr 0.8kWh -2nd hr 0.6kWh -3rd hr	2 h	2 h	3 h	1.5	1.7
Dish washer	TS	0.8kWh-1 h	0.8kWh-1 h 0.6kWh-1 h	0.8kWh - 1 h	1 h	1 h	1 h	0.8	1.4

$$\sum\nolimits_{h=a\ a\in A}^{\beta} x_{h,a} = E_a, \forall a \in P, N \tag{20}$$

For power shift-able and Non-shift-able appliances there will be a predetermined energy E_a which is given by user, the total daily energy consumption for an appliance should be in between time interval α and β should be equal to E_a. In previous technique above constraint is commonly taken for shift-able appliances, but it is not applicable for time shift-able appliances. We cannot supply flexible power between the time intervals provided by consumer. We can only shift the time of usage without changing its own power consumption pattern

$$\begin{aligned} s_a &= \left[s_{a,1}, s_{a,2}, s_{a,3} \cdots s_{a,24}\right]^T;\ s_a \in \{0,1\}^{24}. \\ 0 \le s_a &\le 1; \quad 1^T s_a = 1 \\ X &= P_a^T s_a\ \forall a \in T \end{aligned} \tag{21}$$

$P_a = \left[p_{a,1}, p_{a,2}, p_{a,3} \cdots p_{a,24}\right]^T$ is fixed power consumption pattern

The constraint mentioned above cannot be formulated using Linear Programming [11] method as in previous technique. Since our objective function and constraints consists of both integer and non-integer variables Mixed Integer Linear Programming method is suitable for solving this problem.

Table 4 shows the preferences by three users for 24 h load scheduling. Mixed Integer Linear Programming method has been chosen for solving this problem. We have 577 variables including objective function (peak load), 24 linear inequality constraints, 162 linear equality constraints with boundary conditions.

9 Conclusion

In this work, the authors have proposed and implemented Residential Energy consumption scheduling techniques, to reduce the energy consumption costs, minimize the Peak Average Ration (PAR) as well as Peak load by shifting the heavy loads form peak hours to off peak hours. All the techniques are implemented with case studies using MATLAB Optimization Toolbox with different programming methods. This work was extended to multiple energy sources, industrial load for commercial usage. Communication between users can be introduced through smart grid advanced technology so that users can involve more into these programs. Important conclusions of the techniques are given below

No	Technique	Objective	Optimization Method	Conclusion
1	Energy consumption scheduling of a Residential network	PAR	Linear Programming	Peak load is reduced from 7.27kWh to 1.69Kwh PAR is reduced from 4.55 to 1.69 Heavy load(PHEV) is scheduled in 3 different zones of the day to reduce peak load
2	Energy consumption scheduling of a Residential network	Energy Consumption cost	Quadratic Programming	Total Energy consumption cost is reduced from Rs 221.59 to Rs 53.57 PAR is also reduced from 4.55 to 1.96
3	Mixed Integer Linear Programming technique Energy consumption scheduling	Peak load	Mixed Integer Linear Programming	Hourly peak load is reduced to 3.68 and PAR to 1.73 More suitable for practical appliances Time shift-able and low energy required appliances are scheduled in off-peak hours

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