RESIDENTIAL ENERGY CONSUMPTION SCHEDULING TECHNIQUES

A project Report submitted in partial fulfillment of the requirements

For the award of the degree of

(MASTER OF TECHNOLOGY IN

POWER SYSTEMS AND POWER ELECTRONICS

and

BACHELOR OF TECHNOLOGY IN ELECTRICAL ENGINEERING)

By

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INDIAN INSTITUTE OF TECHNOLOGY MADRAS

May 2014

CERTIFICATE

This is to certify that the project report entitled "**Residential Energy Consumption Scheduling Techniques**" submitted by **J Santosh Kumar (EE09B085**) is a bonafide record work carried out by him at power systems Laboratory**,** Department of Electrical Engineering, Indian Institute of Technology Madras, in partial fulfilment for the award of degree of Dual Degree, **MASTER OF TECHNOLOGY** in power systems and power electronics and **BACHELOR OF TECHNOLOGY** in Electrical Engineering. The contents of this report have not been submitted to any other Institute or University for the award of any degree or diploma.

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ACKNOWLEDGEMENT

I wish to express my deep sense of gratitude and indebtedness to my project guide,

Dr. K. S. Swarup, Professor in Department of Electrical Engineering, for his most valuable guidance, discussions, suggestions and encouragement, from the conception to the completion of this project. His moral support, unreserved co-operation and generosity, which enabled me to complete the work successfully, will be everlasting in my memory.

I would also like to thank my professors and friends from my undergraduate studies while at Indian Institute of Technology, Madras. The preparation and experience I gained were invaluable.

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 in peak hours is becoming larger than off-peak hours, this is the major reason for inefficiency in generation capacity. Generation sector is facing important challenges both in quality and quantity to meet the increasing requirements of consumers. Due to the involvement of smart grid technology in Demand Side Management programs, it has become 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 has opportunities to employ different pricing schemes which will also help in increasing the efficiency of appliances scheduling techniques. Optimal energy consumption scheduling reduces the peak load demand in peak hours, peak average ratio also minimizes the energy consumption cost. In this work, 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.

Key words: Demand side management, optimal energy consumption scheduling, peak load demand, smart grid, power system optimization, energy pricing.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABBREVIATIONS

DSM	Demand Side Management
PAR	Peak Average Ratio
PHEV	Plug in Hybrid Electric Vehicles
DR	Demand Response
DLC	Direct Load Control
EWH	Electric Water Heater
TSO	Transmission System Operator
DSO	Distribution System Operator
NS	Non Shiftable
TS	Time Shiftable
PS	Power Shiftable
ECS	Energy Consumption Scheduler

CHAPTER1

INTRODUCTION

1.1 PROJECT MOTIVATION

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 hours 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 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.

1.2 OBJECTIVE AND SCOPE OF PROJECT

The objective of this project is to implement Residential energy consumption techniques which aim to increase efficiency of power generation by reducing the energy consumption costs, minimizing the PAR as well as Peak load by shifting the heavy loads form peak hours to off peak hours. These techniques are implemented in Matlab optimization tool box for small residential network and they can be further extended to commercial loads.

1.3 THESIS STRUCTURE

Chapter2 gives an introduction about DSM and explains the importance of Demand response in DSM programs and some of DSM strategies are mentioned.

Chapter3 is Residential Energy consumption scheduling Technique for multiple load and single user with PAR minimization, taken a case study and results are provided.

Chapter4 is Residential Energy consumption scheduling Technique for multiple load and single user with Energy Cost minimization, taken a case study and results are provided.

Chapter5 is Mixed integer linear programming Technique for energy consumption scheduling for single user, taken a case study and results are provided.

Chapter6 is Mixed integer linear programming Technique for energy consumption scheduling for multiple households, taken a case study and results are provided.

Chapter7 concludes the thesis.

CHAPTER2

DEMAND SIDE MANAGEMENT

2.1 INTRODUCTION

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.

Shiftable applainces are two types i) Power shiftable and ii) Time shiftable

For power shiftable appliances we can vary the energy supply within standby power limits according to the availability of generation, but for Time shiftable 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 customers 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".

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.

2.2 BENEFITS OF DEMAND RESPONSE [9]

Uncertainty and Variability are inherent to power system network, rapid changes in load demand threaten grid integrity and stability.

Demand response

1) Reduces the uncertainties by decreasing peak demand
2) Increases grid reliability
3) Reduces energy cost
4) Optimizes the energy consumption (Efficiency)

2.3 MAIN PARTICIPANTS OF DR

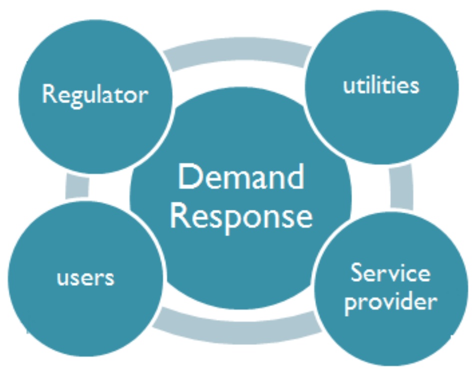

Figure 2.1 Demand Response Participants

Regulator: Makes policies and adopt effective measures to direct power Grid Company, equipment suppliers and power customers to participate in DR.

Utilities: Develop technical standards and establish DR management platform and electric energy service platform.

Service Providers: provide DR equipment and technical services to direct users to participate in DR program in a better way.

And **users** participate in the Demand response programs.

Some of the Demand response options which can be useful in Residential energy consumption scheduling techniques are:-

Table 2.1 Demand response programs

S.no	DR programs	Description
1	Direct Load control	Utilities remotely controls the operations and energy consumption Of certain house hold appliances
2	Interruptible load	Some loads will be subjected to curtailment under tariff or contract
3	Emergency Demand Response	Reduction in the energy supply during an emergency event which combines Direct load control with specified high price This program is more suitable for commercial loads
4	Critical peak pricing	During system contingencies or high wholesale prices for utilities, they will offer price reduction to users for reducing energy consumption
5	Time-of-use pricing	Usually utilities charge average price for some months but in this program average unit prices varies frequently.
6	Real-Time pricing	Retail prices fluctuates hourly or more often to reflect changes in wholesale prices on day or hour ahead

2.4 DEMAND SIDE MANAGEMENT STRATEGIES

Direct load control:

As mentioned earlier, utilities directly control some appliances in our home so that they can maintain balance in supply and demand, also they can maintain frequency balance whenever using renewable sources for power generationSome of the appliances that can be controlled in DLC methods are lighting, water heater, ventilating, air conditioning, refrigerator and pumps.

Direct Load Control method for Electric Water heater [3]:

$$P_{rem}(t) = \frac{e_{rem}(t)}{t_c - t} = \frac{1}{t_c - t}\left\{e_{req} - \int_{t_s}^{t} p_a(t')dt'^{1}\right\} \quad (2.1)$$

$$\gamma(t) = \frac{P_{rem}(t)}{P_{on}}, \; t_{nex} = t_{pre} + \Delta t \quad (2.2)$$

$P_{rem}(t)$ is remaining power consumption, γ is remaining power consumption ratio, t_c and t_s are start time and end time of the consumption.

The information flows between EWHS's and system operators (TSO: Transmission system operator, DSO: Distribution system operator), each EWH calculates and sends $P_{rem}(t_{nex})$ and $\gamma(t_{nex})$ by the above equations.

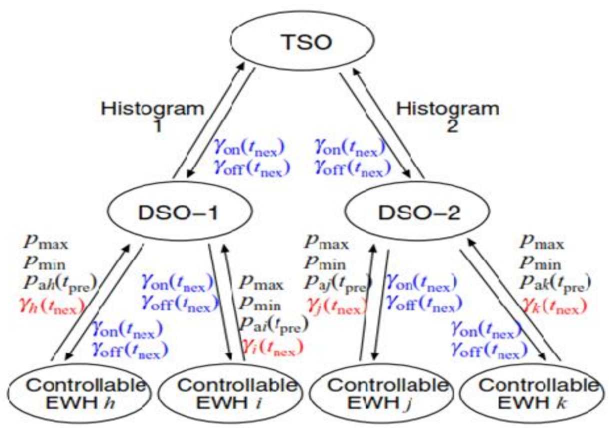

Figure 2.2 Information flows for DLC of EWH

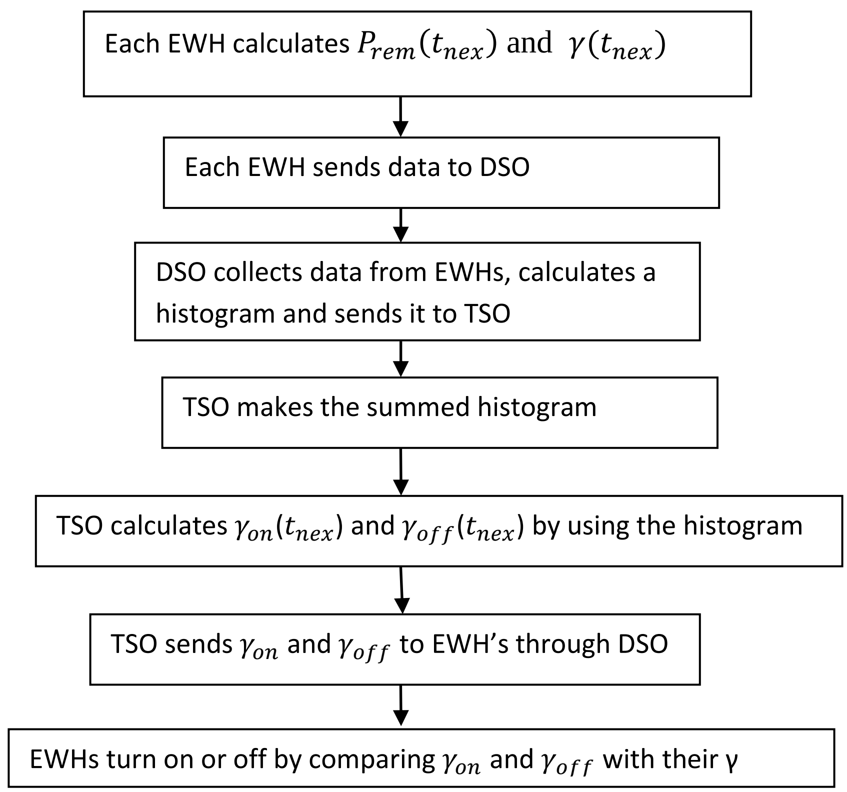

Figure 2.3Flow chart for DLC algorithm

Sometimes users may get privacy problems which are problem for implementing DLC programs. An alternative for DLC is smart pricing, where users are encouraged to voluntarily manage their loads by reducing their energy consumption at peak hours. In this regard, critical peak pricing, Real time pricing, Time-of-use pricing are the popular options available for residential consumers.

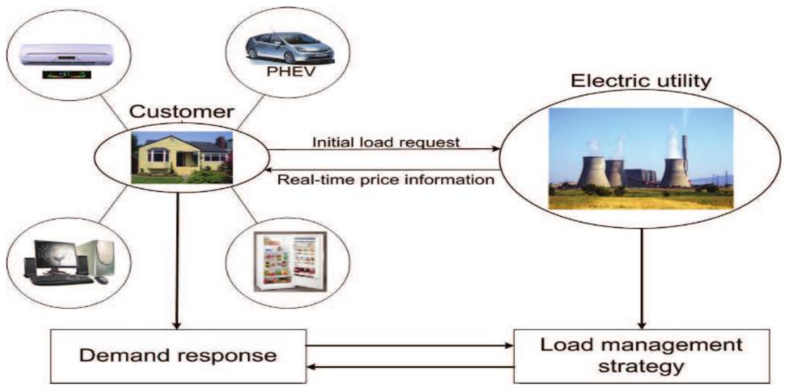

Figure 2.4Load management for price based demand response models

Real Time Pricing model:

Real Time pricing programs can lead to both economic and environmental advantages when compared to flat rates. They provide users an opportunity to reduce their energy consumption costs by responding to pricing that varies with different times of the day. But due to the lack of awareness among users about how to respond to these programs participation is less.

Following is the example for Real time pricing model [4]

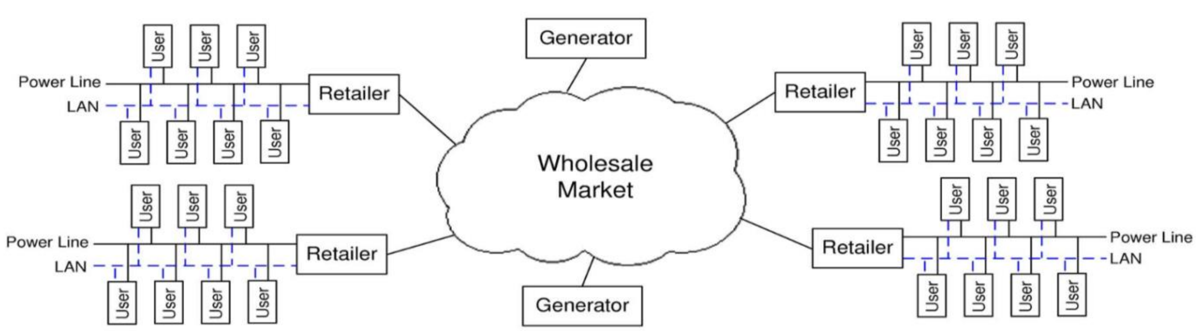

Figure 2.5Real time pricing model [4]

In the above network is a wholesale electricity market formed by multiple generators and retail companies. Each retailer provides electricity for users. Retailers are connected to LANs (Local Area Network) which are used to announce real time pricing to the users.

Residential network model in which Demand side management is by a Third party (company):

In this model we consider a third party managing the energy consumption of multiple users, it gets information from the users and formulate optimization objectives such as maximizing utility, minimization of costs, Reducing peak load, PAR minimization etc. and schedules the usage of loads according to the users preference. Third party combines total load demand from all the users and sends to the Energy source (utility) and collects price information from it.

In this method [5] third party schedules by formulating two objectives

i) Maximization of utility

ii) Minimization of energy costs

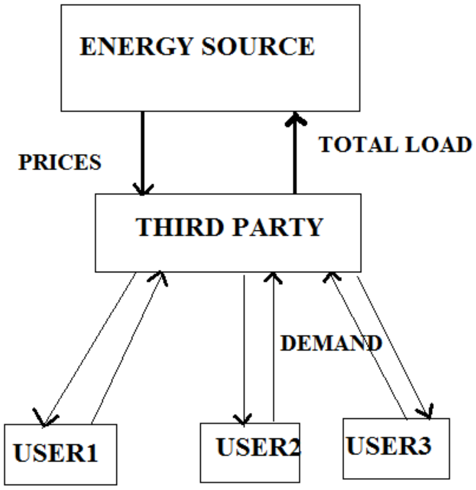

Figure 2.6Energy scheduling model with third party

Formulated Constrained Multi-Objective optimization problem for solving the above objectives

Demand side management strategy for the smart grid with interactions among users and the utility company

Mostly DSM programs based on the interaction between users and utility, but in this model each user interacts with utility and also other users. These types of models help in developing energy consumption games which motivates users to participate, due to the recent advancement in smart grid technologies the interactions need not to be manual, can be automatic through two way digital communication.

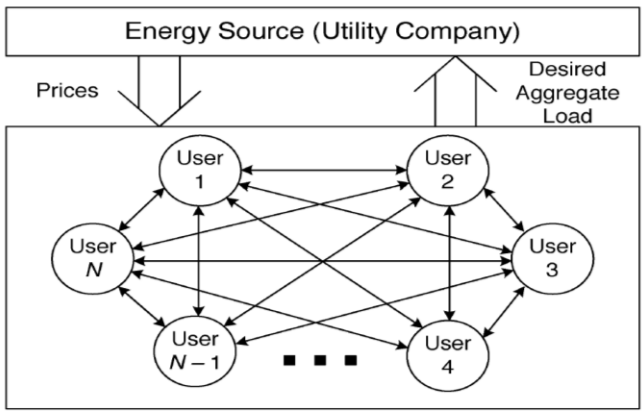

Figure 2.7DSM strategy with user interaction

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

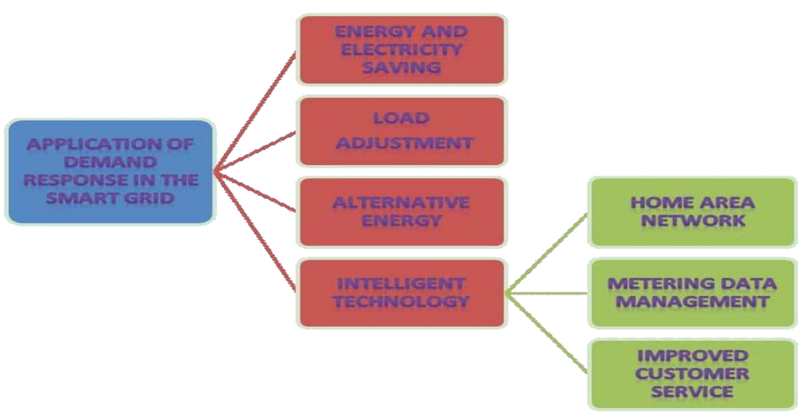

Figure 2.8 Research about Demand response under the smart grid environment

CHAPTER 3

ENERGY CONSUMPTION SCHEDULING OF A RESIDENTIAL NETWORK WITH MULTIPLE LOADS AND ONE ENERGY SOURCE

3.1 SYSTEM MODEL

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.

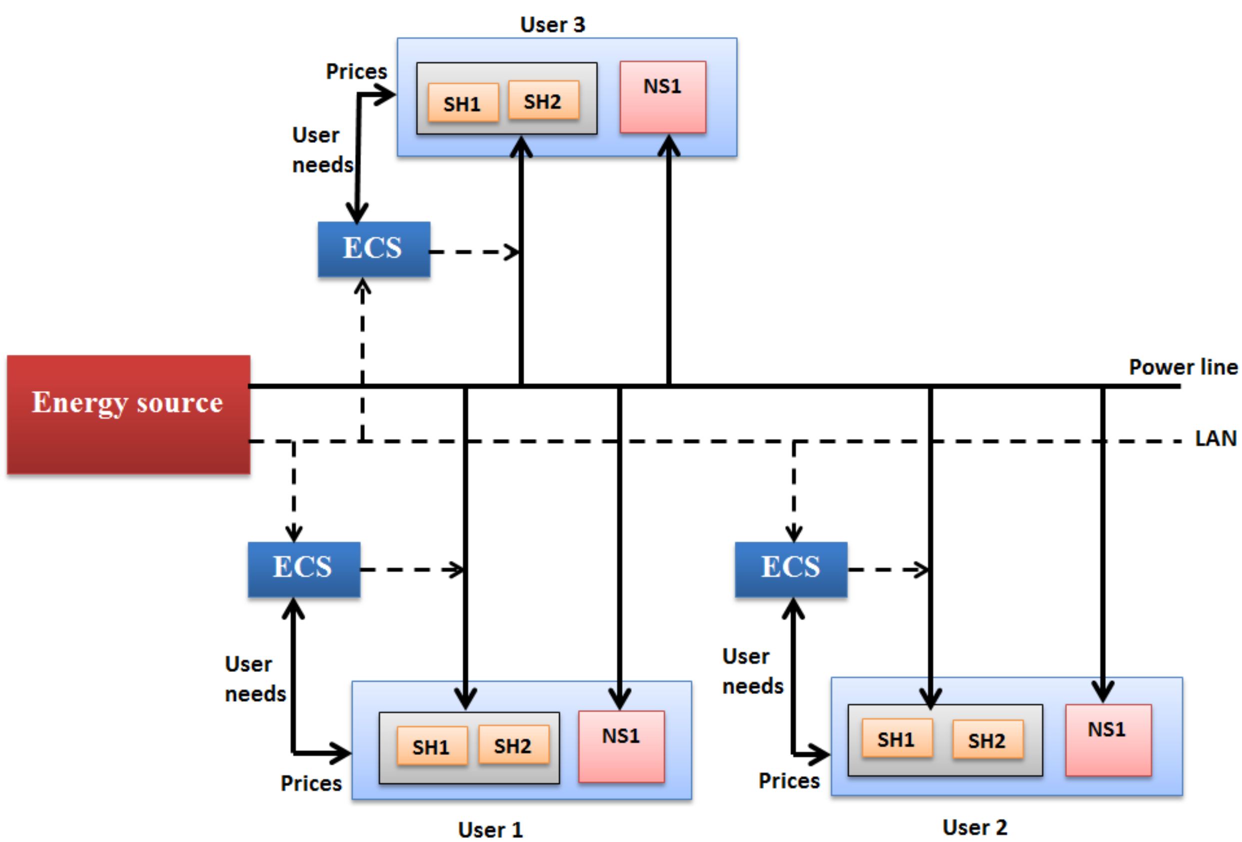

Figure 3.1 Energy consumption scheduling model with 3users each having 3 appliances

In our model we considered 3 users, each having set of appliances differentiated as shiftable and Nonshiftable loads. ECS units can alter only the power supplied to the shiftable 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 Є Ɲ, (Ɲ is set of users and the number of users is N) have set of household appliances denoted with A_n. For each appliance a Є A_n we will have an energy consumption scheduling vector

$$X_{n,a} = \left[x_{n,a}^1, x_{n,a}^2 \dots , x_{n,a}^H \right] \quad \text{here H is total no of hours}$$

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

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

In this technique our objective function is to **minimize PAR (Peak Average Ratio)**

3.2 PEAK AVERAGE RATIO [6]

$$\text{PAR} = \frac{\text{Daily peak load}}{\text{Average Peak Load}} = \frac{L_{peak}}{L_{avg}}$$

$$= \frac{\max_{h \in H} L_h}{\frac{\sum_{h \in H} L_h}{H}}$$

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

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

l_n^h - Total load at hour h

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

l_n - Daily load for user n (for all hours)

L_h - Total load of all users at each hour of the day

$L_h = \sum_{n \in N} l_n^h$

L_{peak} - Daily peak load

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

L_{avg} - Average load

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

$E_{n,a}$ - Predetermined total daily energy consumption

3.3 PROBLEM FORMULATION

Objective function: Peak Average Ratio Minimization

$$\underset{X_n \forall\, n \in N}{\text{minimize}} \ \frac{H \ max_{h \in H}(\sum_{n \in N} \sum_{a \in A_n} x_{n,a}^h)}{\sum_{n \in N} \sum_{a \in A_n} E_{n,a}} \qquad (3.1)$$

Constraints:

1) $\alpha_{n,a} < \beta_{n,a}$ (3.2)

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.

2) $\sum_{h=\alpha_{n,a}}^{\beta_{n,a}} x_{n,a}^h = E_{n,a}$ (3.3)

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 $E_{n,a}$.

3) $x_{n,a}^{h}$=0 (3.4)

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

4)$\beta_{n,a}$- $\alpha_{n,a}$≥Time interval needed to finish the operation (3.5)

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

5) $\sum_{h\in H} L_h = \sum_{n\in N} \sum_{a\in A_n} E_{n,a}$ (3.6)

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

6) $\gamma_{n,a}^{min} \leq x_{n,a}^{h} \leq \gamma_{n,a}^{max}$ (3.7)

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 (1) 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

$$\underset{X_n \forall\, n \in N}{\text{minimize}} \ \max_{h\in H}\left(\sum_{n\in N} \sum_{a\in A_n} x_{n,a}^{h}\right) \qquad (3.8)$$

The above objective function (8) contains two functions (min and max) it is difficult to optimize so it can be further simplified as

$$\underset{X_{n\, \forall\, n\in N}}{\text{minimize}} \ L \qquad \text{Subject to} \quad L \geq \sum_{n\in N} \sum_{a\in A_n} x_{n,a}^{h} \ \text{ and the above constraints}$$

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 I have chosen MATLAB optimization tool box which has linear programming method in it.

3.4 GENERAL FORMULATION FOR OPTIMIZATION IN LINEAR PROGRAMMING METHOD (MATLAB) [10],[11]

$$\min_x f^T x \quad \text{Such that} \begin{Bmatrix} A.x \leq b \\ Aeq.x = beq \\ lb \leq x \leq ub \end{Bmatrix}$$

f, x, beq, lb,and ub are vectors and A, Aeq are matrices

$A.x \leq b$ for inequality constraints, $Aeq.x = beq$ for equality constraints and $lb \leq x \leq ub$ for bounded constraints

Command line: [x f_{val}] = lin prog(f, A, b, Aeq, beq, lb, ub)

3.5 CASE STUDY

We considered 3 users each having 3 appliances model with 2 shiftable and 1 Nonshiftable loads. ECS cannot schedule Nonshiftable appliances, some of them are Heater, Hob, micro oven, Refrigerator, freezer, electric stove and lighting for some standard bulbs etc. Shiftable 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 3.1 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	10^{th} and 20^{th} 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 shiftable or Nonshiftable. Data is provided by the users to the utility at the beginning of the day for the schedule of that particular day.

Table 3.2 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	

Note: NS - Nonshiftable, SH- shiftable

For all Nonshiftable appliances 24hours (whole day) given as the time preference, users want these appliances to be ON continuously, standby power is taken as $(\frac{\text{predetermined Energy}}{\text{time interval}})$

i.e. user 1's Nonshiftable appliance standby power = $(\frac{1.32}{24})$ =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

3.6 RESULTS

1) Energy consumption of users before scheduling (data taken from table3.1) is shown in Fig 3.2, we can see that Peak load is very high because users consumed their energy randomly and there is huge overlap in the usage of heavy loads.

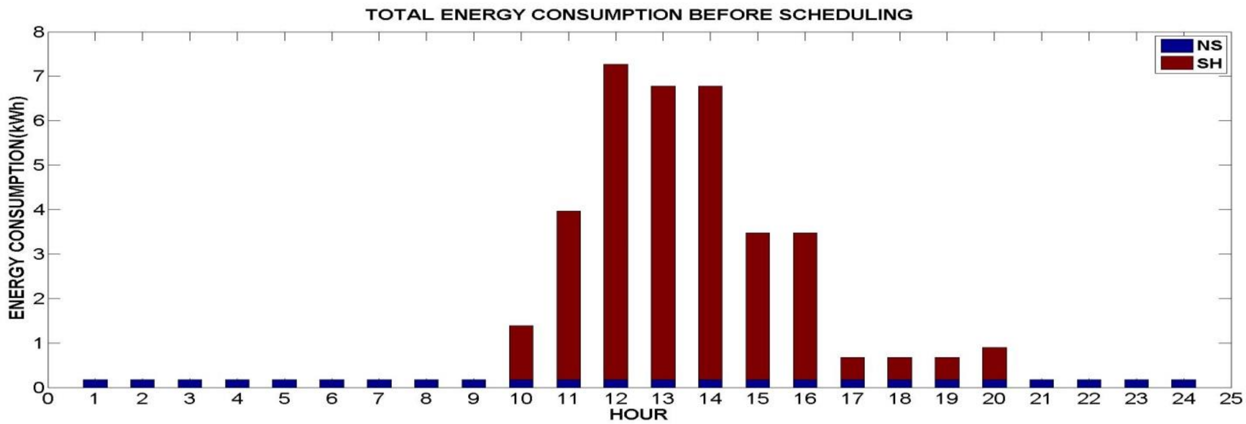

Figure 3.2Energy consumption of users before scheduling (when ECS units are not used)

Average load =1.59, Peak load = 7.27, Peak Average Ratio = 4.55

2) Energy consumption of users after scheduling is shown in Fig 3.4. peak load is reduced to 1.69 and PAR to 1.06, since usage of heavy load appliances is scheduled with out overlapping the peak load and PAR are highly improved. There is no change in the usage of Nonshiftable applainces.

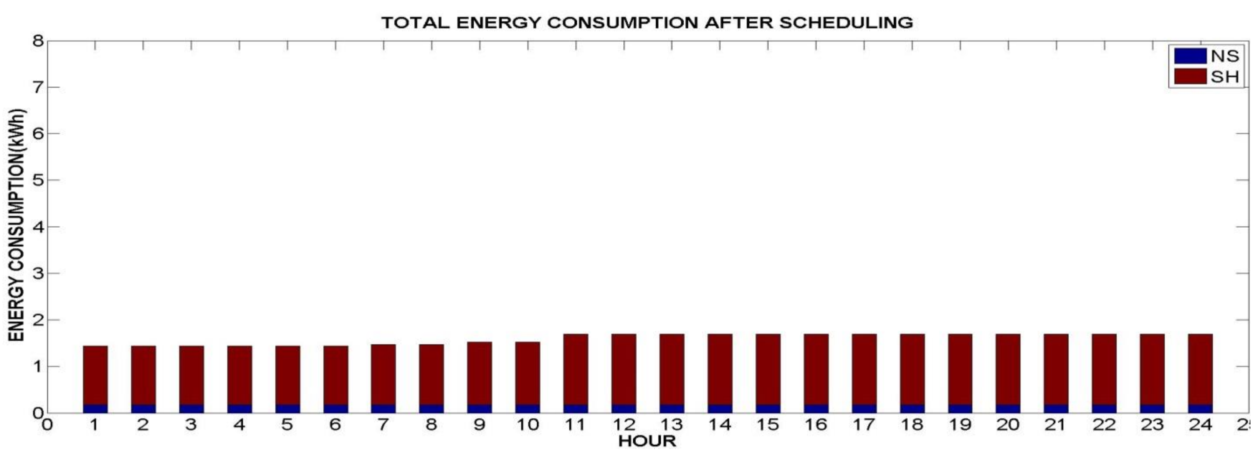

Figure 3.3Energy consumption of users after scheduling (when ECS units are used)

Peak load = 1.69, Average load = 1.59, Peak Average Ratio =1.06

3) Energy schedule comparision between users is shown in Fig 3.4. since we have considered 1 heavy load and 2 light loads for each user, scheduling of heavy is distributed to three different time zones of the day and also considering the users requirement.

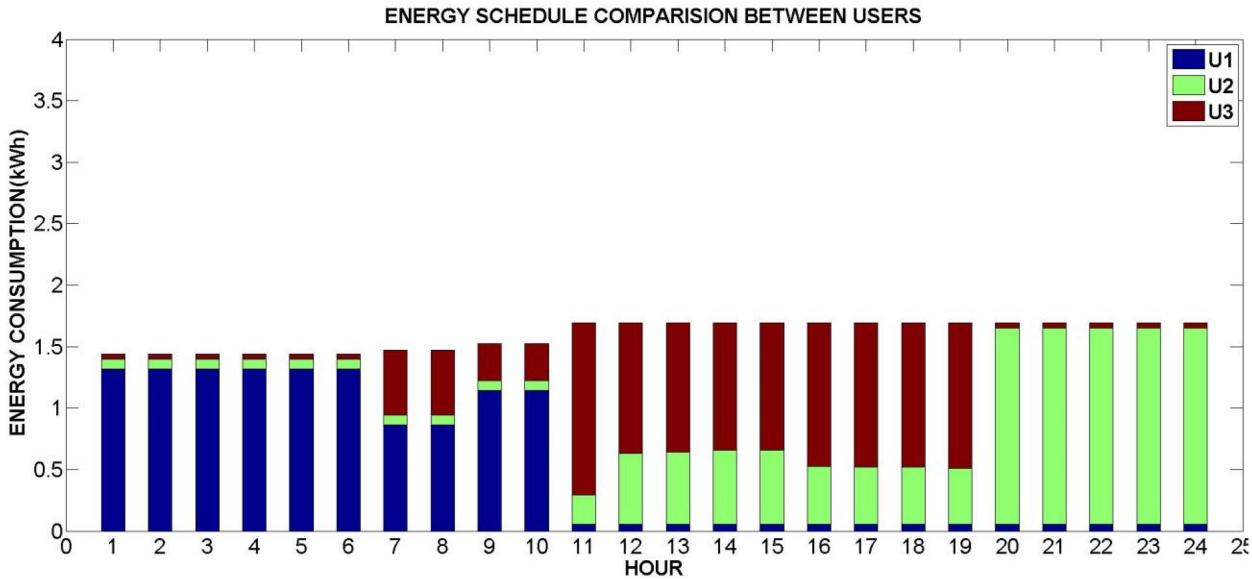

Figure 3.4 Energy schedule comparison between users

4) Energy consumption scheduling of individual users before(fig 3.5, 3.7, 3.9)and after (fig 3.6, 3.8, 3.10) ECS units are deployed, we observed that there is no change usage of Nonshiftable appliances, for every user after scheduling PAR and Peak load is reduced.

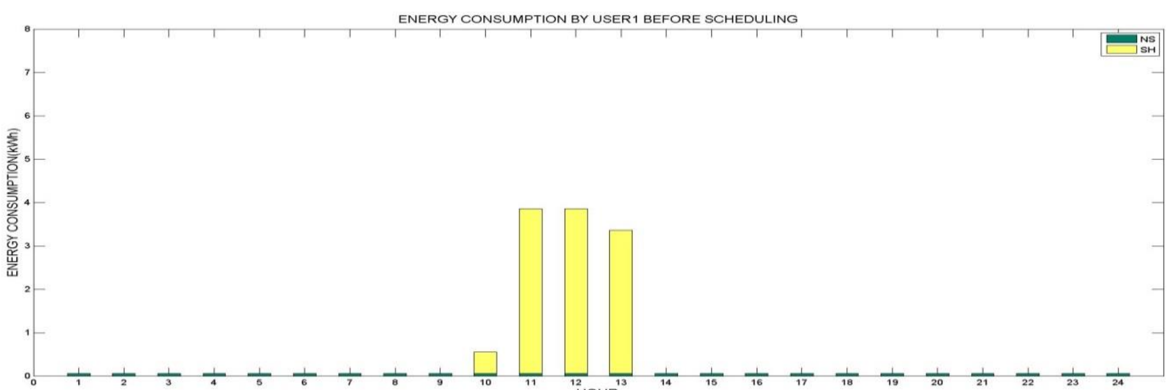

Figure3.5 energy consumption of user1 before scheduling

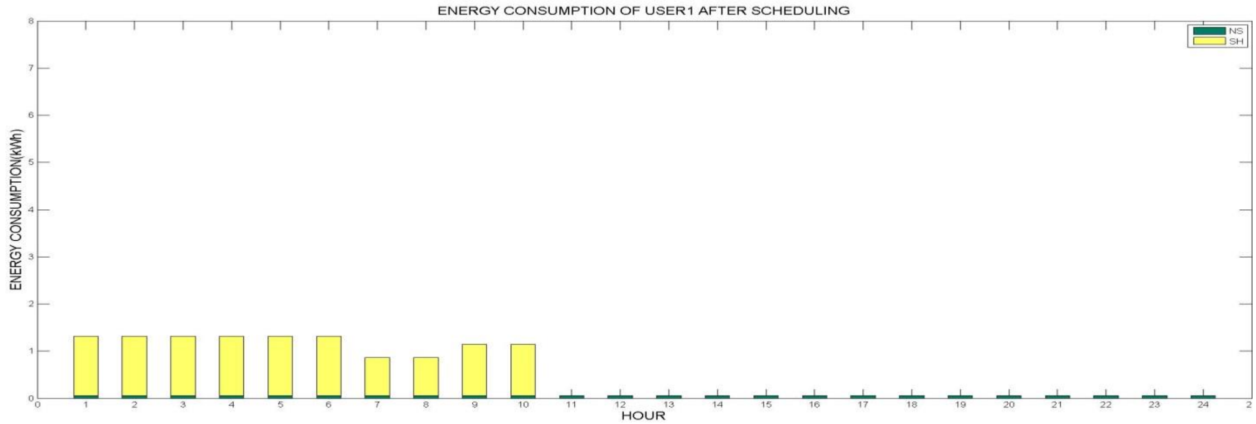

Figure 3.6 energy consumption of user1 after scheduling

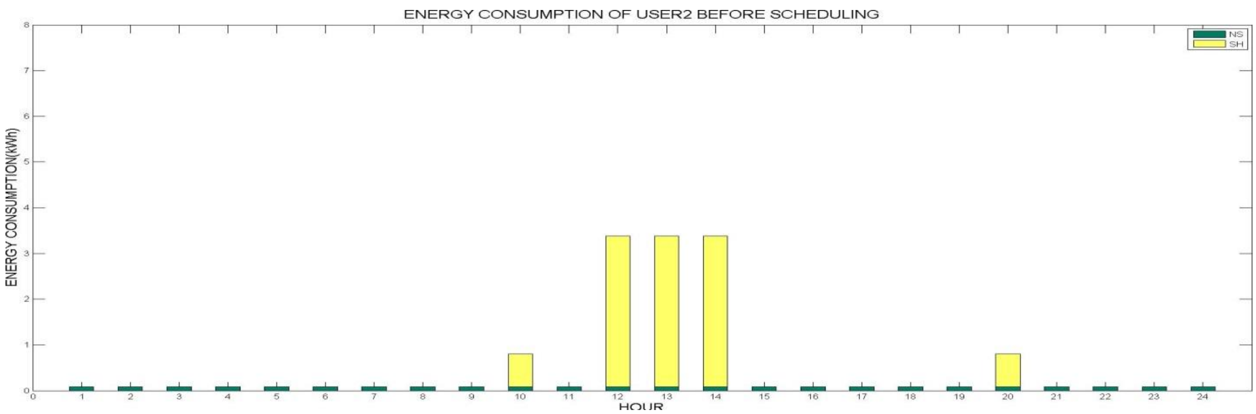

Figure3.7 Energy consumption of user2 before scheduling

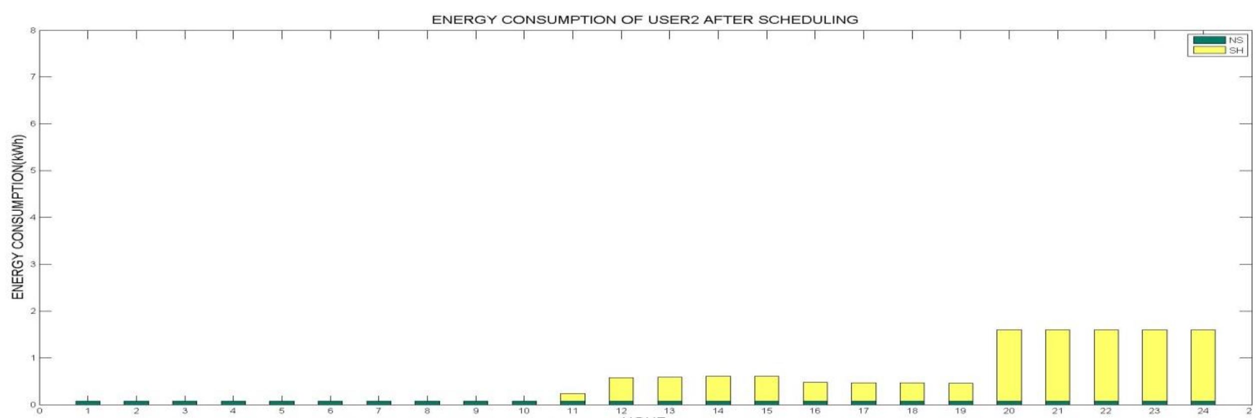

Figure3.8Energy consumption of user2 after scheduling

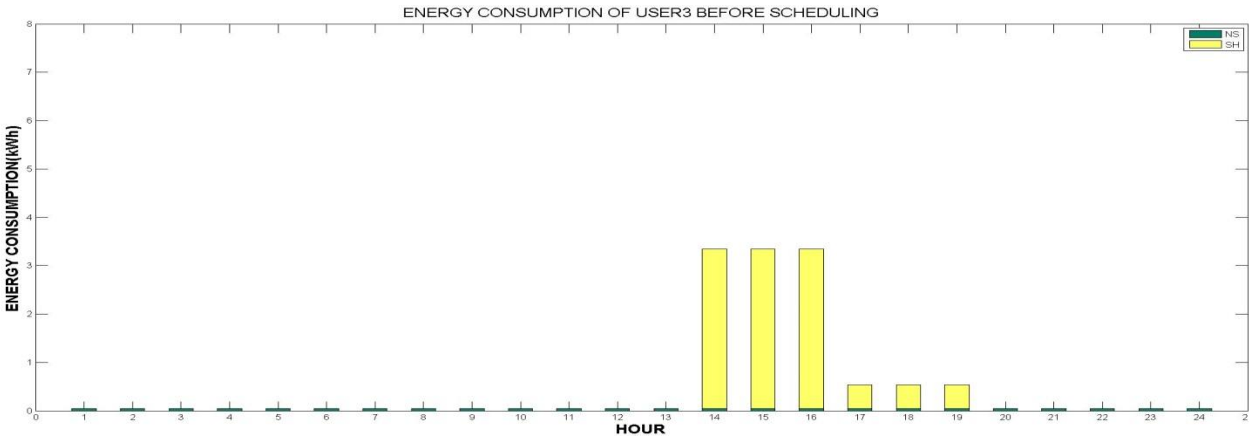

Figure 3.9 Energy consumption of user3 before scheduling

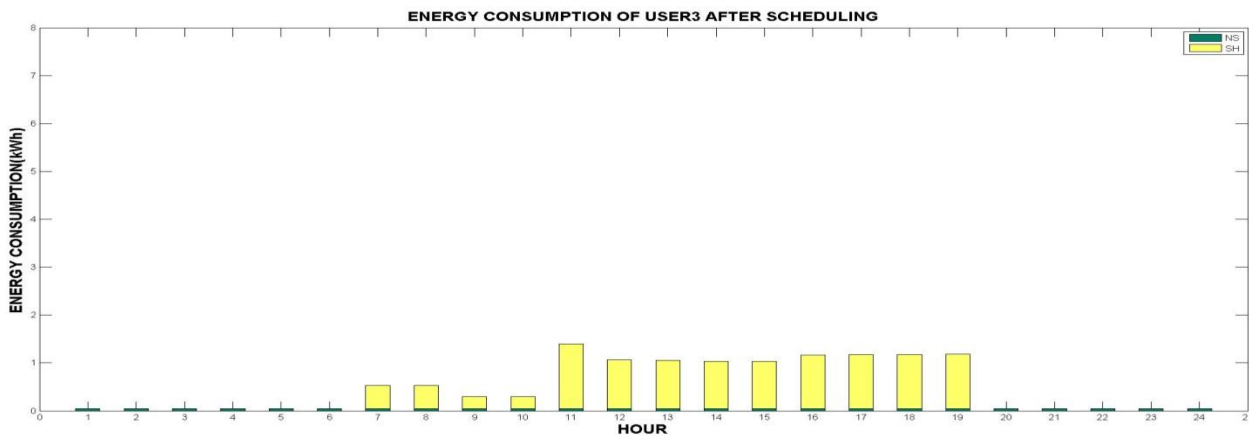

Figure 3.10 Energy consumption of user3 after scheduling

3.7 SUMMARY

1) Energy consumption by Nonshiftable appliances is same before and after scheduling (with and without ECS using units) for total and all individual users.
2) ECS scheduled the usage in order to minimize Total **Peak load** from 7.27kWh to 1.69kWh which is the simplified objective in our technique.
3) **Peak Average Ratio** is reduced from 4.55 to 1.06 which improved the reliability of the network.
4) Users predetermined energy, time preferences and other constraints are also satisfied.
5) In our technique 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.
6) By using this technique utility can satisfy user's requirement without any scarcity.
7) Users cannot directly reduce their energy consumption costs but they will get incentives from the utilities.

3.8 FURTHER DEVELOPMENTS

1) This technique might not be suitable for all appliances in practice because
   Some appliances have a fixed power consumption pattern, it means once the load is turned on, it has to work according to its own power consumption pattern until the job is finished.
2) We considered one energy source only, but it can be extended to multiple energy sources.
3) Average fixed unit price is considered for the whole day in our case study so users cannot decrease their bill amount but they will get incentives from the utility.
4) If there is coordination (communication) between the users they will participate more in the Demand side management techniques.
5) We considered shifting and reducing of energies at particular time, we can involve storing of energy so that consumers sell the energy back to the grid during peak hours.
6) It can be extended to commercial load in industrial region to better the shape of the Load curve.

CHAPTER 4

ENERGY CONSUMPTION SCHEDULING OF RESIDENTIAL NETWORK WITH COST MINIMIZATION

4.1 ENERGY COST MODEL

In this technique 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. In our technique we considered a simple quadratic cost function which represents actual energy cost as for thermal generators [1].

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

$$C_h(L_h^1) < C_h(L_h^2) \quad \text{for all} \quad L_h^1 < L_h^2$$

Energy cost function is $C_h(L_h) = a_h L_h^2 + b_h L_h + c_h$ Where a_h, b_h and $c_h \geq 0$

L_h - Total load of all users at each hour of the day

$$L_h = \sum_{n \in N} l_n^h$$

h - Hour of the day

l_n^h - Total load at hour h

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

$x_{n,a}^h$ - Hour energy consumption by an appliance

$$L_h = \sum_{n \in N} \sum_{a \in A_n} x_{n,a}^h$$

From above

$$C_h(L_h) = a_h L_h^2 + b_h L_h + c_h \quad (4.1)$$

$= a_h(\sum_{n \in N} \sum_{a \in A_n} x_{n,a}^h)^2 + b_h(\sum_{n \in N} \sum_{a \in A_n} x_{n,a}^h) + c_h$, we neglected c_h.

4.2 PROBLEM FORMULATION FOR COSTMINIMZATION

Objective function: Energy consumption cost minimization

$$\underset{X_n \forall\, n \in N}{\text{minimize}} \sum_{h=1}^{H} C_h(\sum_{n \in N} \sum_{a \in A_n} x_{n,a}^h)$$

Constraints: Equations (3.2) to (3.7)

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 which has Quadratic programming method in it.

4.3 GENERAL FORMULATION FOR OPTIMIZATION IN QUADRATIC PROGRAMMING METHOD (MATLAB) [10], [11]

$\min_x \frac{1}{2} x^T H x + f^T x$ Such that $\begin{Bmatrix} A\,.\,x \le b \\ Aeq.\,x = beq \\ lb \le x \le ub \end{Bmatrix}$

H, *A*, and *Aeq* are matrices, and *f*, *b*, *beq*, *lb*, *ub*, and *x* are vectors.*f*, *lb*, and *ub* can be passed as vectors or matrices. $A\,.\,x \le b$ is for inequality constraints, $Aeq.\,x = beq$ is for equality constraints and $lb \le x \le ub$ is for bounded constraints

Command line

opts = optimoptions('quadprog','Algorithm','active-set','Display','off');

[x,fval,exitflag,output,lambda] = quadprog(H,f,A,b,Aeq,beq,lb,ub,[],opts);

4.4 CASE STUDY

We considered 3 users each having 3 appliances which same as previous technique

Data for Energy consumption before scheduling is given in the Table 3.1

Data for Preferences given by the users for scheduling is given in Table 3.2

In our quadratic cost function 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

We got 217 variables including cost minimization objective, 9 equality constraint equations and boundary conditions.

4.5 RESULTS

1) Total energy consumption cost before (fig 4.1) and after (fig 4.2) 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.

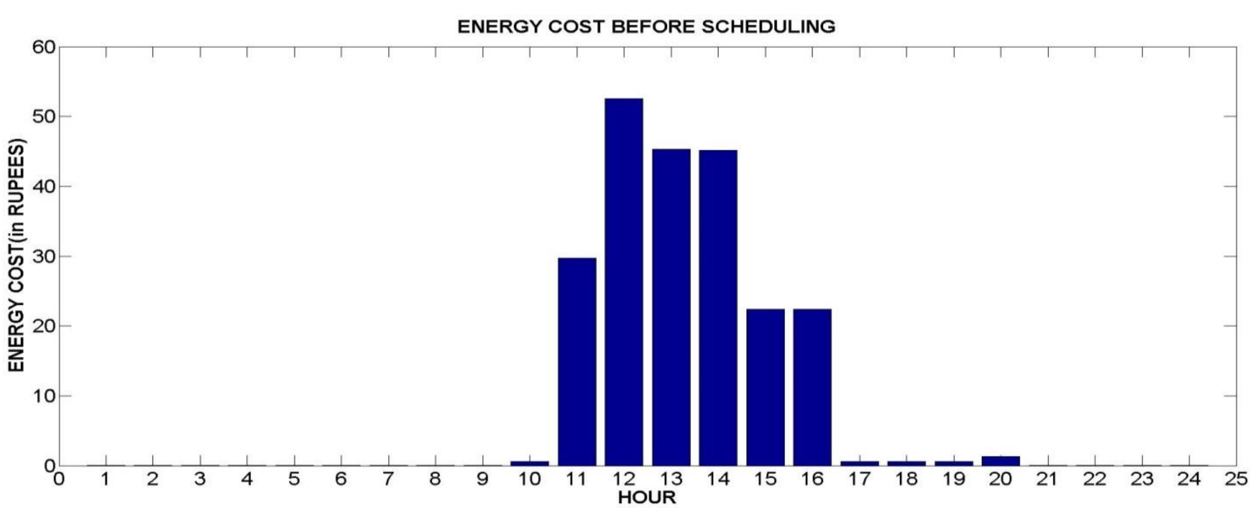

Figure 4.1Total energy cost before scheduling

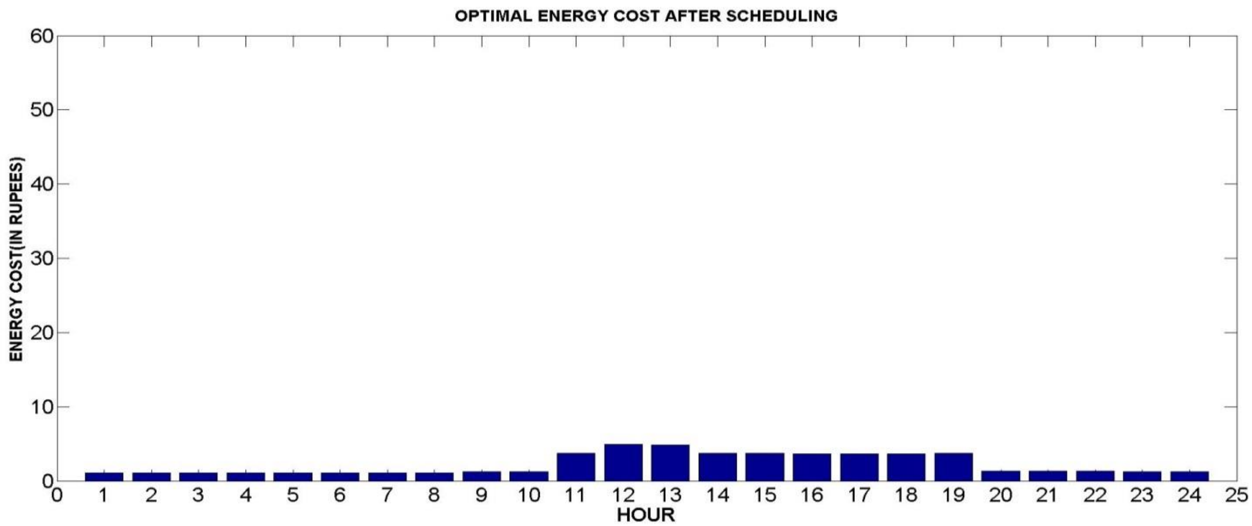

Figure 4.2Optimal energy cost after scheduling

2) Total Energy consumption before (Fig 3.2) and after (Fig 4.3) scheduling with cost minimization. We also interested in observing about PAR with cost minimization as an objective, PAR is reduced from 7.27 to 1.966.

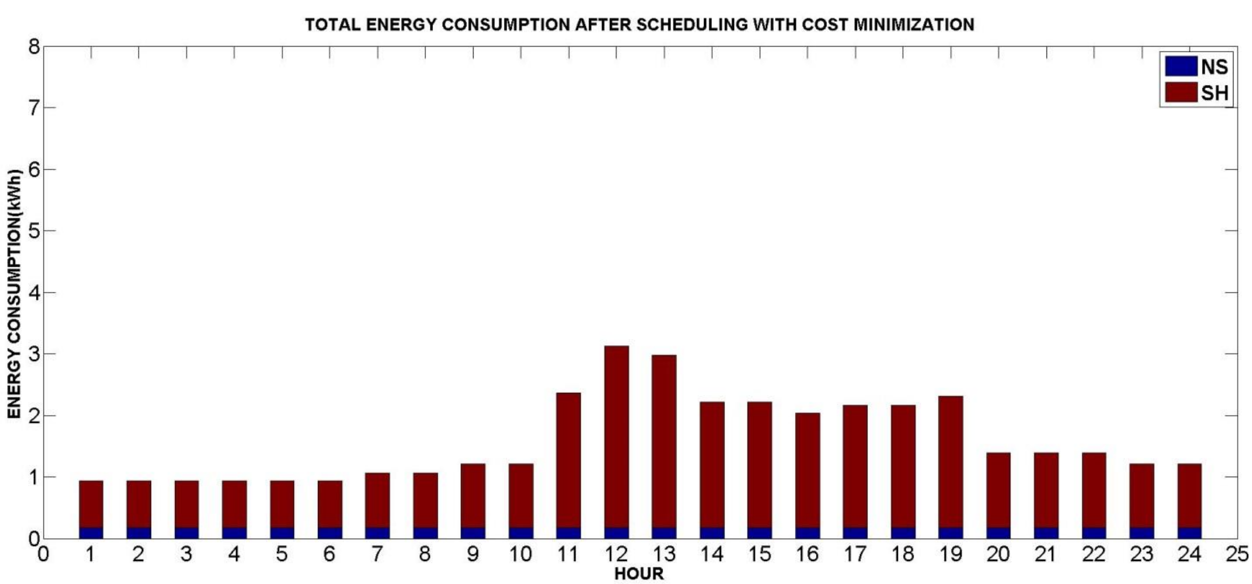

Figure 4.3Energy consumption after scheduling **with cost minimization**

3) Energy consumption cost for individual users before and after scheduling

Energy consumption cost of user1 is reduced from Rs 82.70 to Rs 14.95

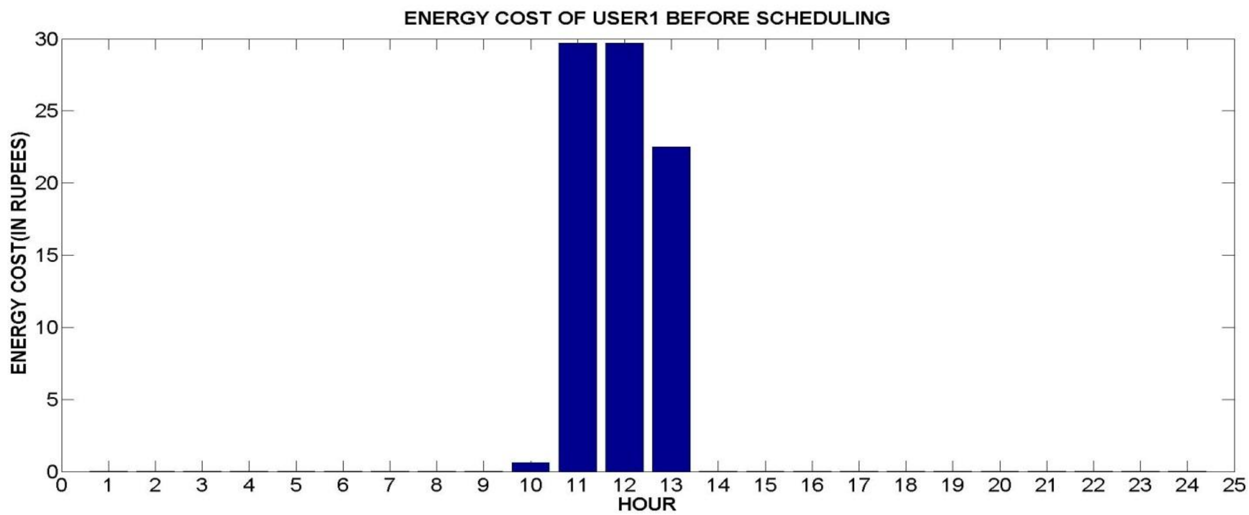

Figure4.4 Energy cost of user1 before scheduling

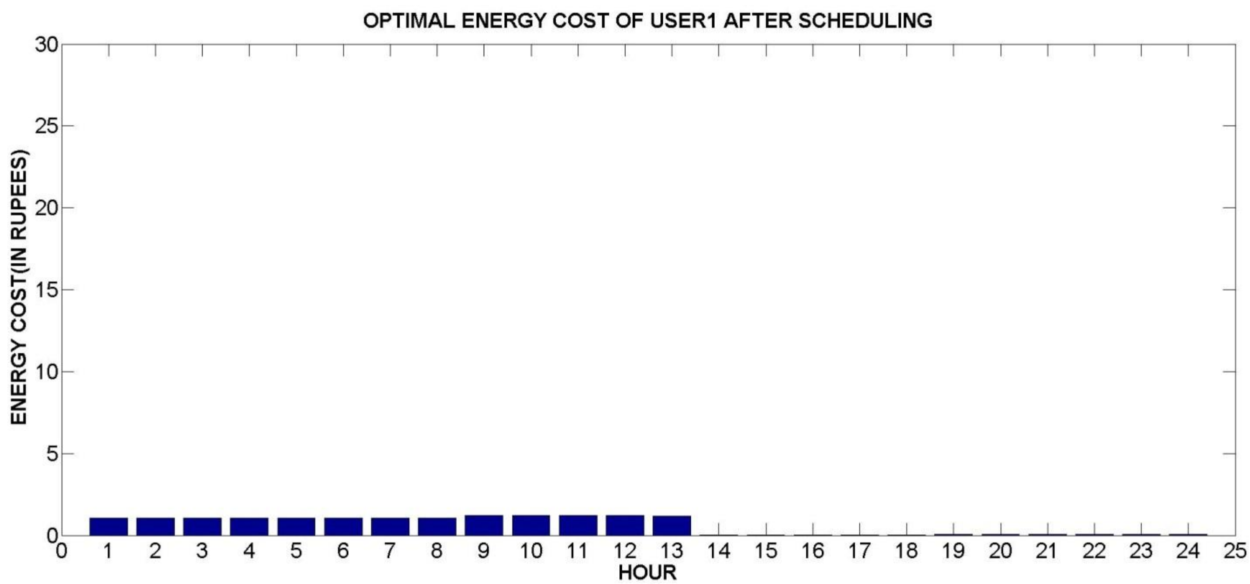

Figure 4.5Energy cost of user1 after scheduling

Energy consumption cost of user2 is reduced from Rs 70.05 to Rs 16.15

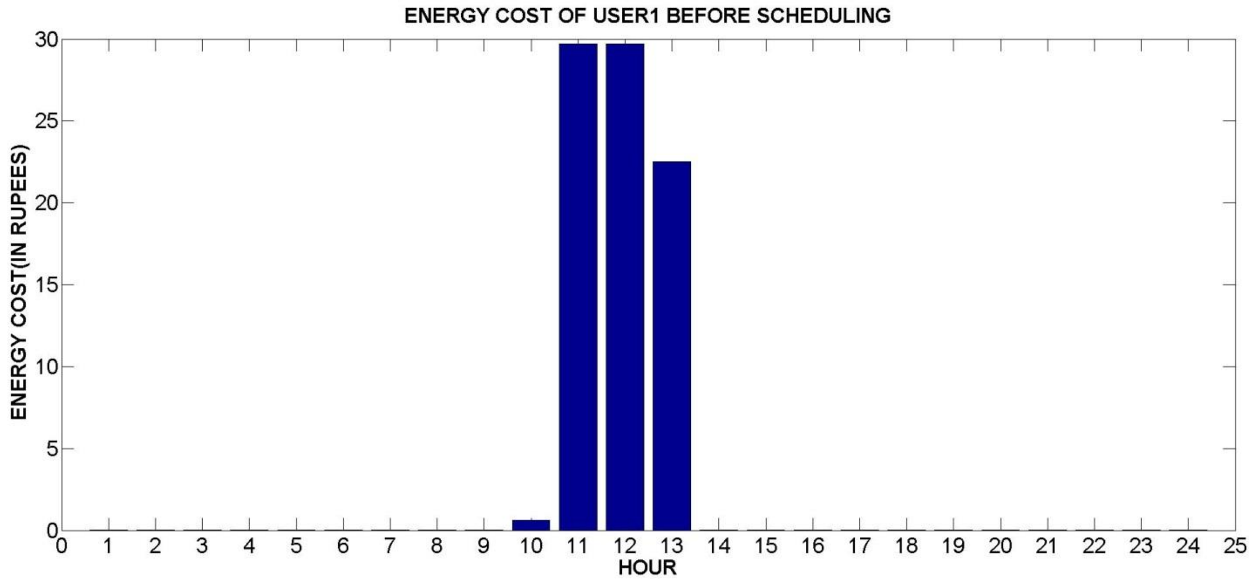

Figure 4.6Energy cost of user2 before scheduling

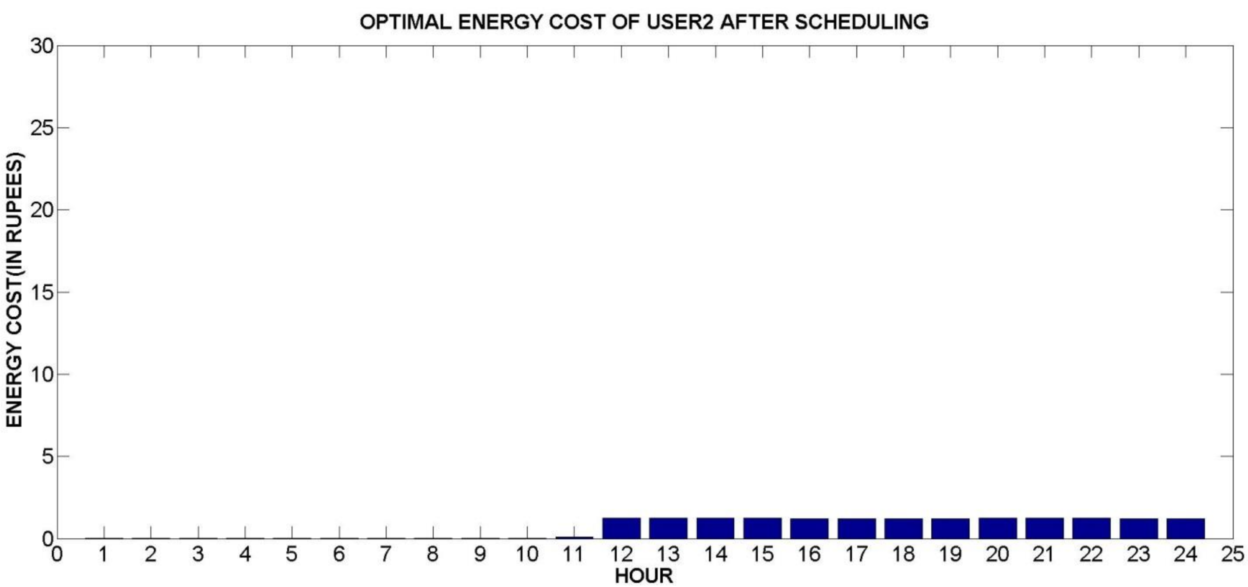

Figure 4.7Energy cost of user2 after scheduling

Energy consumption cost of user3 is reduced from Rs 68.64 to Rs 22.47

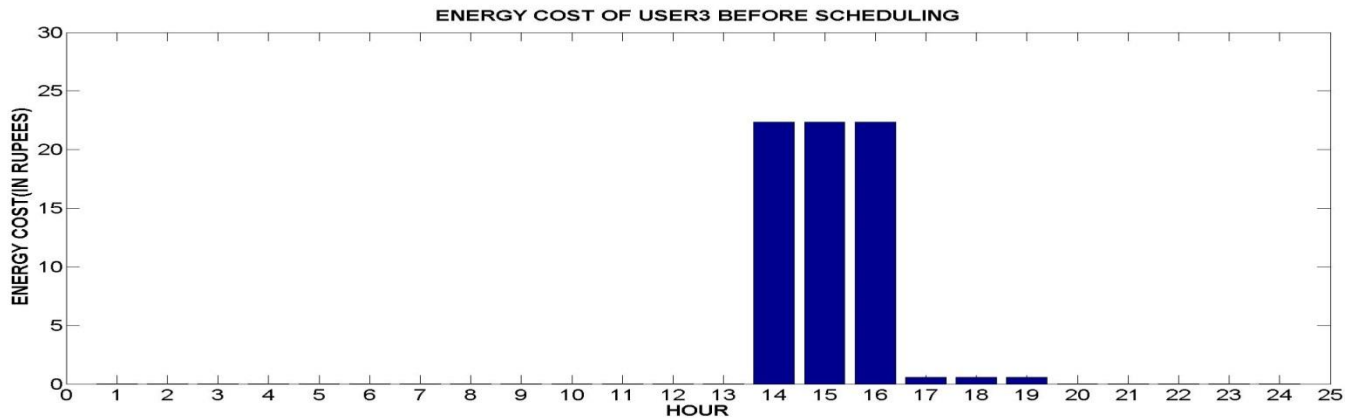

Figure 4.8Energy cost of user3 before scheduling

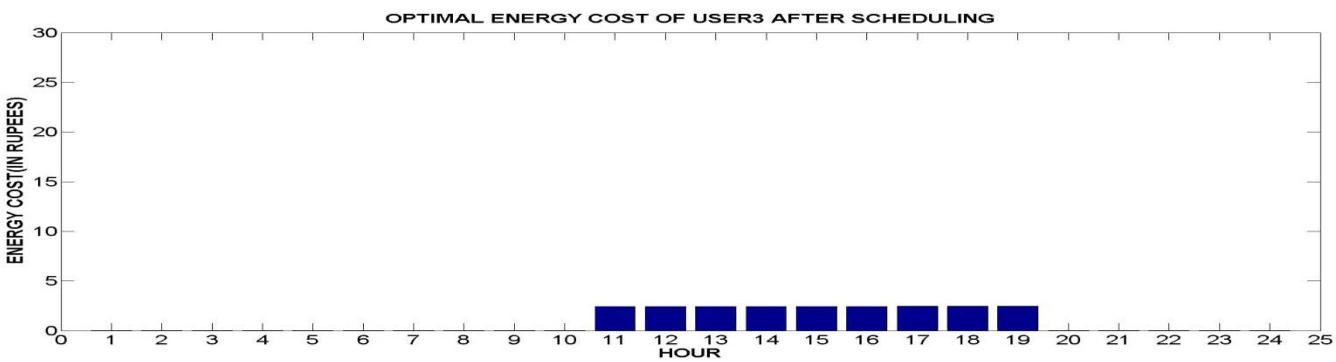

Figure 4.9Energy cost of user3 after scheduling

4) Energy consumption schedule of users before (fig 3.5, 3.7, 3.9) and after scheduling

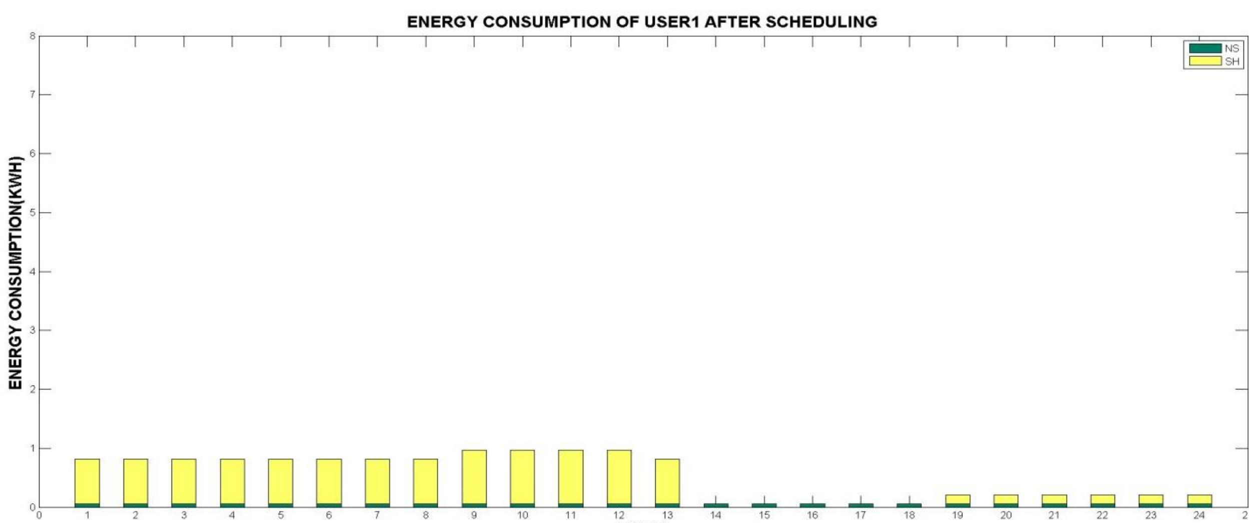

Figure 4.10Energy consumption of user1 after scheduling with cost minimization

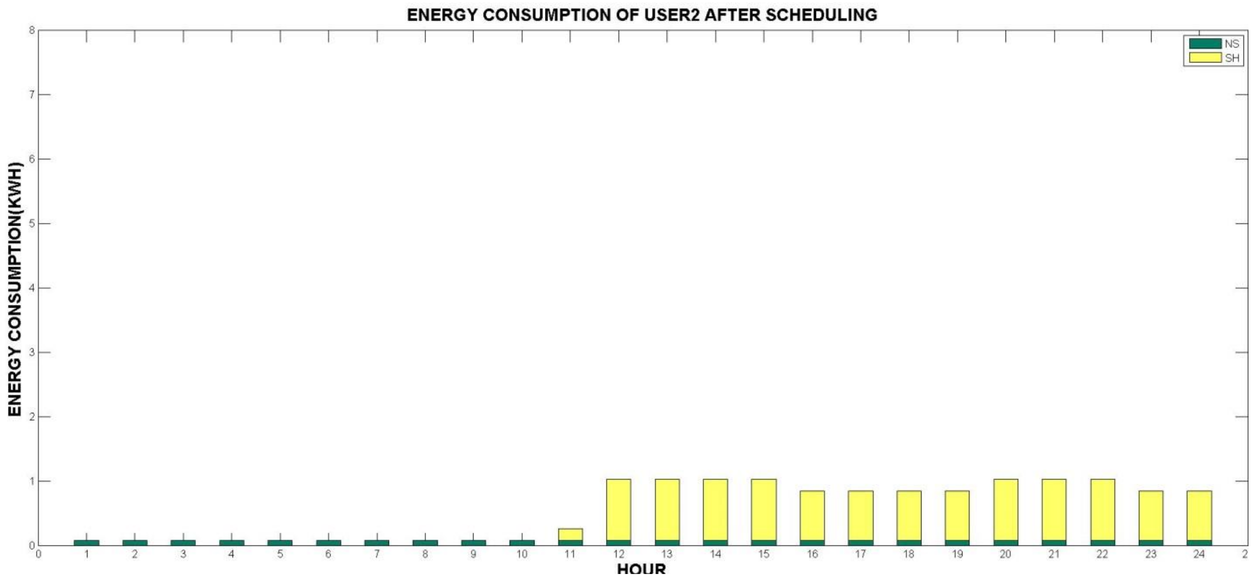

Figure 4.11Energy consumption of user2 after scheduling with cost minimization

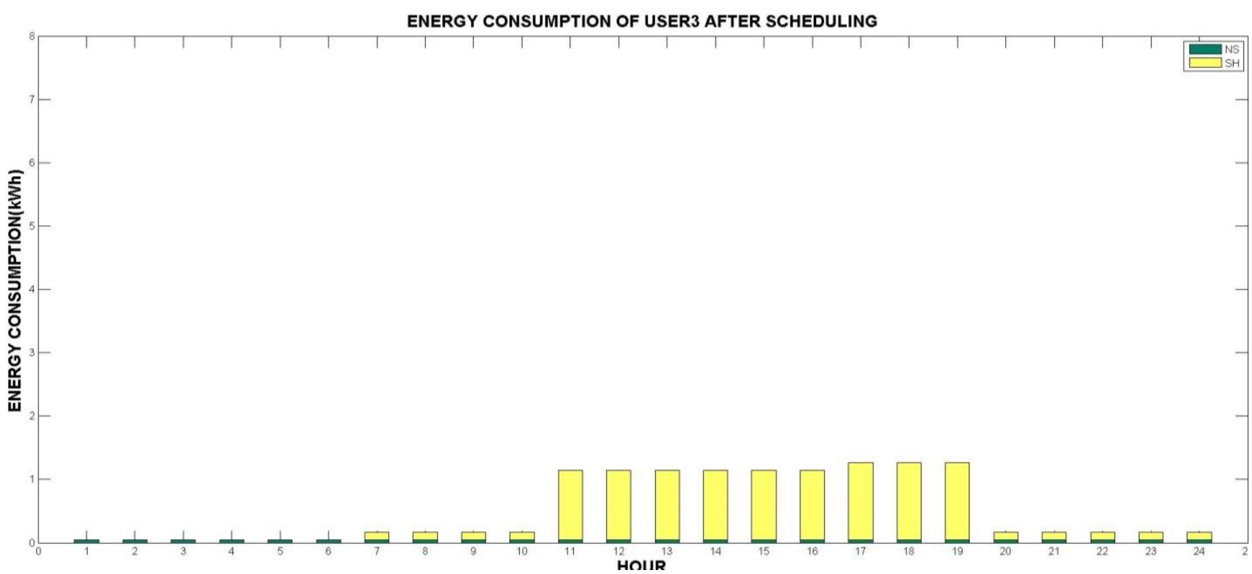

Figure 4.12Energy consumption of user3 after scheduling with cost minimization

4.6 SUMMARY

1) By using this technique the Energy consumption cost for residential network is decreased from Rs 221.59 to Rs 53.57 for 24hours.
2) Since our data consists of 3 users each having 3 appliances and before scheduling data is one of the worst possible case (overlapping of heavy loads consumption for 3 users), so after scheduling there will be very huge amount of decrease in energy consumption cost.
3) Consumers can directly reduce their energy consumption costs, so they will get motivation to participate more in DSM programs.
4) Peak Average Ratio is reduced when users shift their usage of appliances from peak hours to off-peak hours in order to minimize their energy costs, so utilities also get benefit by following this technique.
5) Peak Average Ratio is reduced from 4.55 to 1.96.

CHAPTER 5

MIXED INTEGER LINEAR PROGRAMMING TECHNIQUE FOR ENERGY CONSUMPTION SCHEDULING FOR SINGLE USER

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 Shiftable loads as power shiftable and Time shiftable. 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 shiftable 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 shiftable 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

1. Non shiftable
2. Power shiftable
3. Time shiftable

5.1 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.

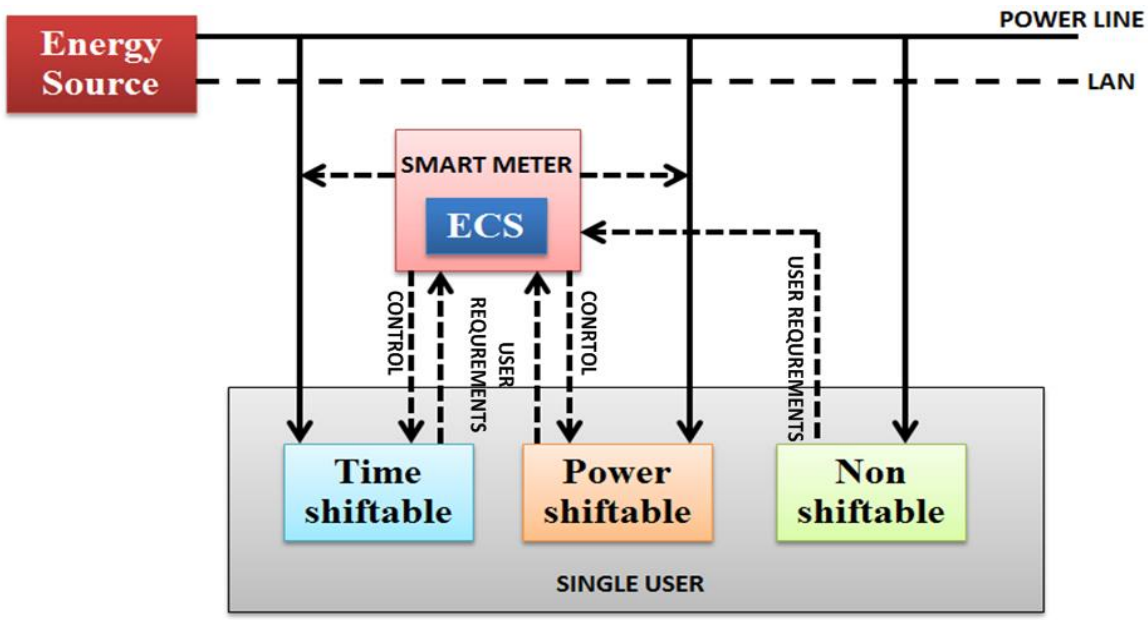

Figure 5.1 Energy schedule model for single user in Residential Network

In the above diagram power will be delivered from power line to the user, in the middle Energy Consumption Scheduler controls Time shiftable and power shiftable according to the user's preference. But cannot schedule or control nonshiftable appliances it only takes requirement from the user.

In our technique we scheduled the energy consumption of user by taking Peak Average Ratio minimization as an objective. 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.

5.2 PROBLEM FORMULATION FOR PEAK LOAD MINIMIZATION

Objective function: Minimization of Peak load L

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

Constraints

1) $\sum_{a \in A} x_{a,h} \leq L, \forall h \epsilon H$ (5.1)

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

2) $x_{a,h} \geq 0$ (5.2)

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

3) $x_{a,h} \geq N_a \ \forall a \epsilon$ N, ∀ hϵ during its preferred working hours (5.3)

   The energy consumed by every Nonshiftable appliance for an hour should be less than its fixed power requirement per hour (N_a)

   So the total predetermined energy for a Nonshiftable appliance is calculated as follows

   $E_{N,a}$ = (no of working hours) x(N_a)

   N is set of Nonshiftable appliances.

4) $\gamma_a^{min} \leq x_{h,a} \leq \gamma_a^{max} \ \forall a \epsilon$ P, ∀ hϵ during its preferred working hours (5.4)

   Energy consumed by a power shiftable 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 shiftable appliances.

5) $\sum_{h=\alpha}^{\beta} x_{h,a} = E_a \ \forall a \epsilon$ P,N (5.5)

   For power shiftable and Nonshiftable 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.

6) In previous technique above constraint is commonly taken for shiftable appliances, but it is not applicable for time shiftable 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

$X_a = P_a^T s_a \ \forall a \in T$ (5.6)

$0 \leq s_a \leq 1$

$1^T s_a = 1$

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

$$P_a = \begin{bmatrix} p_{a,1} & p_{a,24} \cdots & p_{a,3} & p_{a,2} \\ p_{a,2} & p_{a,1} \ \cdot \cdots & p_{a,4} & p_{a,3} \\ & \cdots & & \\ & \cdots & & \\ p_{a,24} & p_{a,23} \ \cdots & p_{a,2} & p_{a,1} \end{bmatrix}, \ X_a = [x_{a,1}, \ x_{a,2}, x_{a,3}, , , , , , , x_{a,24}]^{\ T}, \ \ 1^T = [1, 1, 1, 1 \ldots],$$

$s_a = [s_{a,1}, \ s_{a,2}, s_{a,3}, , , , , , , s_{a,24}]^{\ T}, \ s_a \in \{0,1\}^{24}$

The constraint mentioned above cannot be formulated using Linear Programming 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.

5.3 GENERAL FORMULATION FOR OPTIMIZATION IN QUADRATIC PROGRAMMING METHOD (MATLAB) [10], [11]

Objective function $\min_x f^T x$ subject to $\begin{Bmatrix} x(intcon) are\ integers \\ A\,.x \leq b \\ Aeq.x = beq \\ lb \leq x \leq ub \end{Bmatrix}$ (5.7)

f, *x*, intcon, *b*, *beq*, *lb*, and *ub* are vectors, and *A* and *Aeq* are matrices

command line: X = intlinprog(f,intcon,A,b,Aeq,beq,lb,ub)

5.4 CASE STUDY

We considered a single user having 6 appliances- 2 Nonshiftable, 2 Power shiftable and 2 Time shiftable for 24 timeslots in a day (24 hours)

Table 5.1Preferences given by single user for scheduling [8]

Appliance	**Type**	**Hourly consumption (kWh)**	**Time preference**	**Energy requirement (kWh)**
Fridge	**NS**	**0.12**	**24 hours**	**2.88**
Heater	NS	1	8pm to 10pm 3am to 5am	4
Water boiler	PS	0 – 1.5	24 hours	3
PHEV (15 miles daily)	PS	0.1 - 3	8pm to 8am	5
Washing mc	TS	1kWh for 1st hour 0.5kWh for 2nd hour	2 hours	1.5
Dish washer	TS	0.8kWh for 1hour	1 hour	0.8

We have 193 variables consisting of 144 normal variables, 48 integer variables and an objective variable with constraints and boundary conditions.

5.5 RESULTS

1) Optimal energy consumption schedule of individual appliances (Fig 5.2 to 5.4).

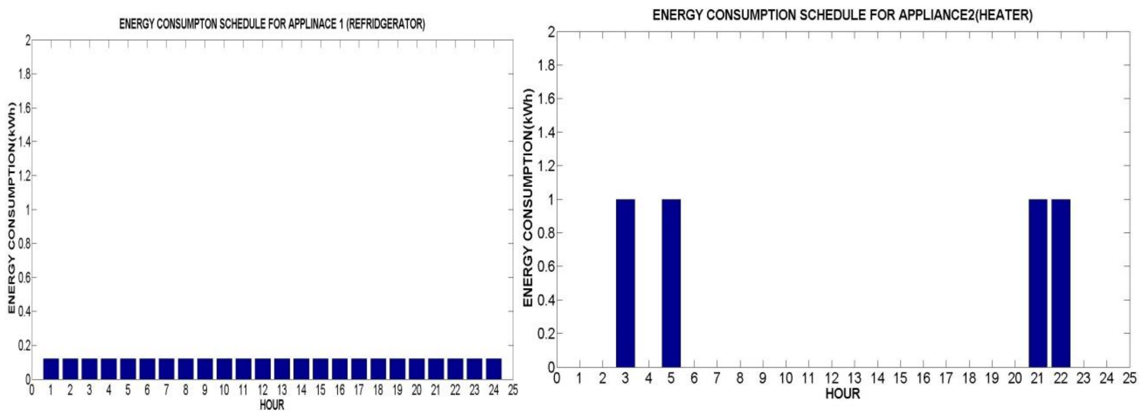

Figure 5.2 Optimal energy consumption schedule for Non shiftable appaliances

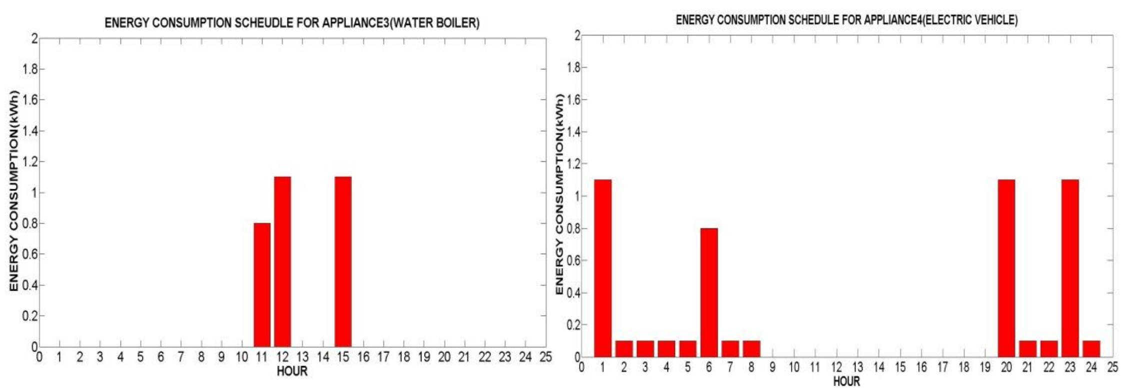

Figure5.3 Optimal energy consumption schedule for Power shiftable appliances

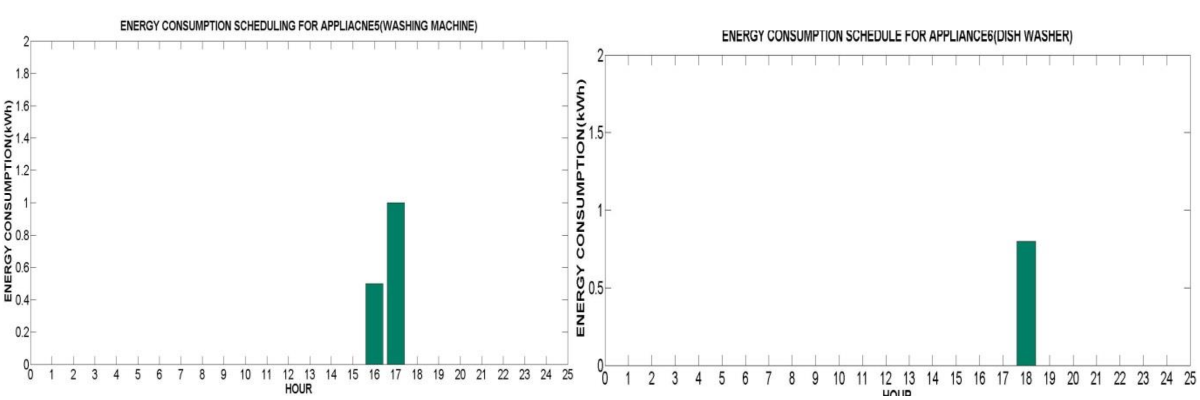

Figure 5.4 Optimal energy consumption schedule for Time shiftable appaliances

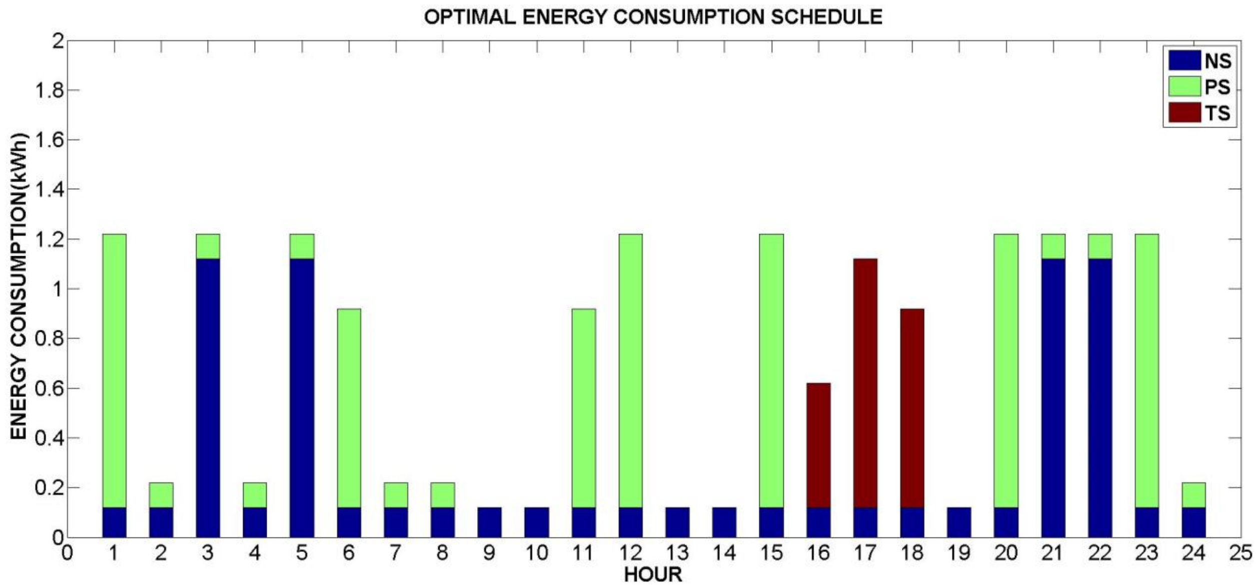

Figure 5.5 Optimal energy consumption schedules for single user

5.6 SUMMARY

1) Hourly peak load is reduced to 1.22
2) In this model the appliances with low energy requirement is scheduled in high peak hours
3) Time shiftable appliances are scheduled to operate in low peak hours i.e. during night hours.
4) In this technique we considered only single source and it can be extended to multiple sources and users.
5) We considered shifting and reducing of energies at particular time, we can involve storing of energy too.
6) If there is any coordination (communication) between the users they will participate more in the Demand side management techniques

CHAPTER 6

MIXED INTEGER LINEAR PROGRAMMING TECHNIQUE FOR ENERGY CONSUMPTION SCHEDULING OF MULTIPLE HOUSEHOLDS

6.1 INTRODUCTION

In our previous chapter we explained the technique of Energy consumption scheduling for single user in a Residential network, we are extending it to multiple households in this chapter. In this technique smart meters of every consumer is connected through LAN, there will be a Central control system which controls all the loads in the system and display results of the schedule to the users in regular intervals. Here we considered same type of appliances for every consumer but the load requirement, power patterns and users preferences are different. We are scheduling by taking minimization of **peak load** as an objective with same constraints as in previous chapter.

We considered 3 users each having 6 appliances for 24 hours schedule. 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

6.2CASE STUDY

Data given by the users for scheduling of their loads for 24hours

Table 6.1 user1's daily preference

Appliance	**Type**	**Hourly consumption (kWh)**	**Time preference**	**Energy requirement (kWh)**
Fridge	NS	0.12	24 hours	2.88
Heater	NS	1	9pm to 10pm 3am to 5am	3
Water boiler	PS	0 – 1.5	24 hours	3
PHEV (15 miles daily)	PS	0.1 - 3	8pm to 8am	5

Washing mc	TS	1kWh for 1st hour 0.5kWh for 2nd hour	2 hours	1.5
Dish washer	TS	0.8kWh for 1hour	1 hour	0.8

Table 6.2 user2's daily preference

Appliance	**Type**	**Hourly consumption (kWh)**	**Time preference**	**Energy requirement (kWh)**
Fridge	NS	0.12	24 hours	2.88
Heater	NS	1	8pm to 10pm 3am to 6am	5
Water boiler	PS	0 – 1.5	8am to 8pm	2
PHEV (12 miles daily)	PS	0.1 - 3	10pm to 8am	4
Washing mc	TS	1kWh for 1st hour 0.7kWh for 2nd hour	2 hours	1.7
Dish washer	TS	0.8kWh for 1hour 0.6kWh for 2nd hour	1 hour	1.4

Table 6.3 user3's daily preference

Appliance	**Type**	**Hourly consumption (kWh)**	**Time preference**	**Energy requirement (kWh)**
Fridge	NS	0.14	24 hours	3.36
Heater	NS	1	7pm to 9pm 4am to 7am	5
Water boiler	PS	0 – 1.5	24 hours	3
PHEV (9 miles daily)	PS	0.1 - 3	10pm to 8am	3
Washing mc	TS	1.2kWh for 1st hour 0.8kWh for 2nd hour 0.6kWh for 3rd hour	3 hours	1.7
Dish washer	TS	0.8kWh for 1hour	1 hour	1.4

6.3 RESULTS

1) Optimal energy consumption schedule for the multiple households is shown in fig 6.1. Peak load is 73% more than the average load which can be improved by taking more users. We observed that the preferences given the users are absolutely satisfied.

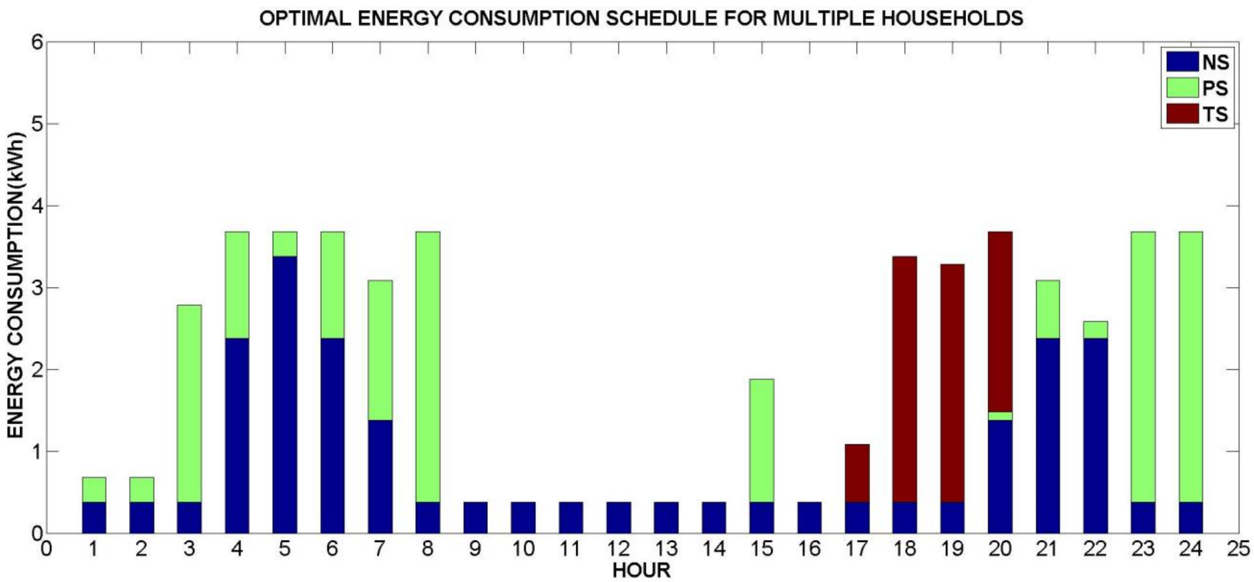

Figure 6.1Optimal energy consumption for multiple households

Peak = 3.68

Daily Average = 2.12

Peak Average Ratio = 1.73

2) Optimal energy consumption schedule for individual users

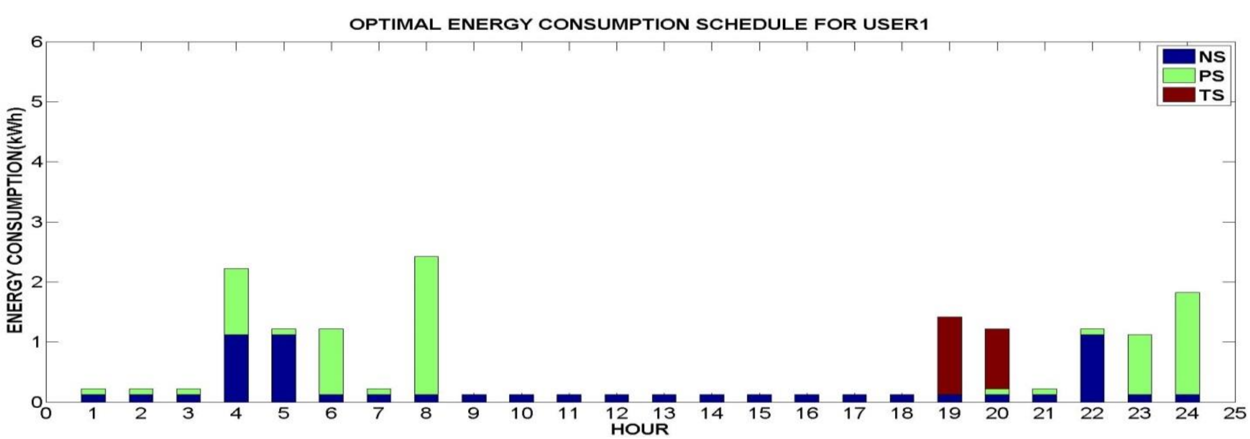

Figure 6.2Optimal energy consumption for user1

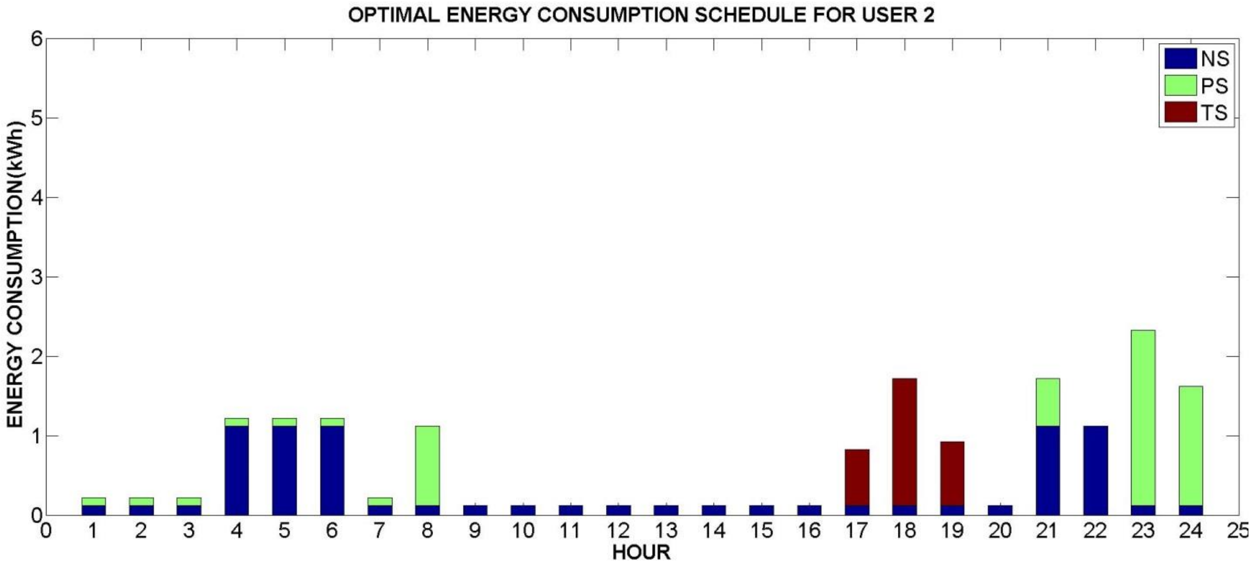

Figure 6.3Optimal energy consumption for user2

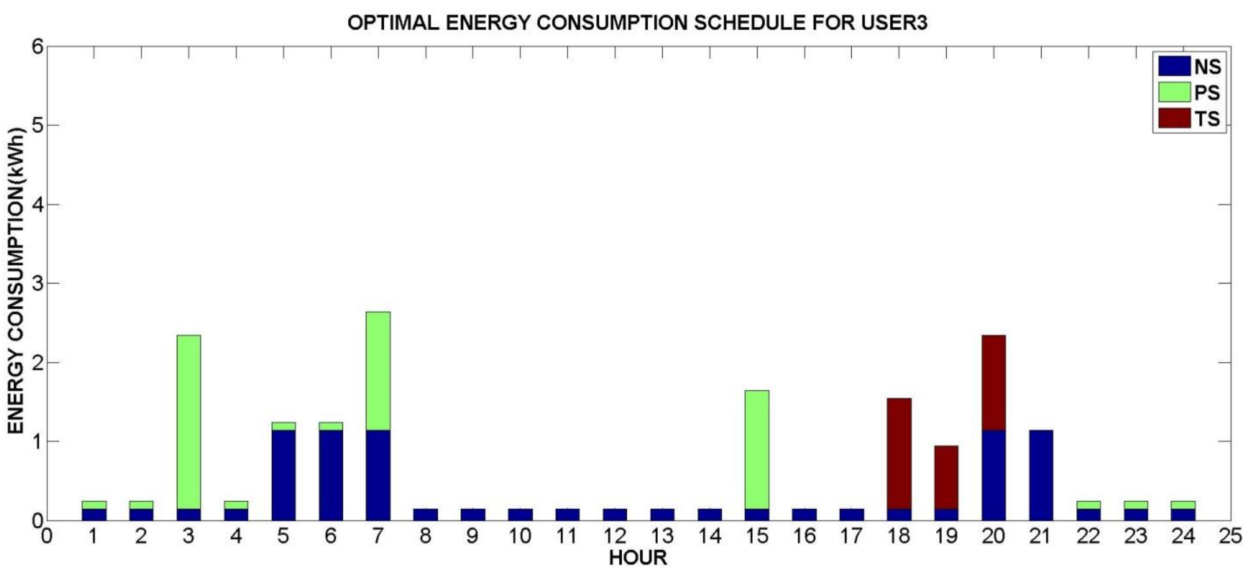

Figure 6.4Optimal energy consumption for user3

6.4 SUMMARY

1) Peak load is reduced to 3.68 and PAR to 1.73, which means peak load is 73% higher than the daily average.
2) We can obverse from results that the preferences given by users are satisfied.
3) Since most of the time preferences given by consumers are overlapping the reduction in the peak is not great, if we consider more consumers for the study it would have been improved.
4) In our case study the power requirement by Nonshiftable appliances is more so there is not much improvement in the peak load reduction.
5) As we have chosen Peak load as an objective, consumers cannot decrease their energy cost directly but they will get incentives from the utility.

CHAPTER 7

CONCLUSION

In our work we have been implemented 4 Residential Energy consumption scheduling techniques, these techniques reduce the energy consumption costs, minimize the 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.

Table7.1Residential Energy Consumption Techniques

S.NO	TECHNIQUE	OBJECTIVE	PROGRAMMING METHOD IN MATLAB	RESULTS
1	Energy consumption scheduling of a Residential network	PAR	Linear Programming	PAR is reduced from 4.55 to 1.06
2	Energy consumption scheduling of a Residential network	Energy cost	Quadratic Programming	Energy cost is reduced from Rs 221.59 to Rs 53.57
3	Mixed Integer Linear Programming technique Energy consumption scheduling for single user	Peak load	Mixed Integer Linear Programming	Hourly Peak load is reduced to 1.22
4	Mixed Integer Linear Programming technique Energy consumption scheduling for multiple Households	Peak load	Mixed Integer Linear Programming	Hourly peak load is reduced to 3.68 and PAR to 1.73

In our case studies for first two techniques we took the worst case that happen when users randomly consumes energy without any knowledge of DSM programs, so results of optimization are very great. Our third technique is more suitable for all the appliances in practice, we extended it to multiple household.

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