An Efficient HEMS for Demand Response considering TOU Pricing Scheme and Incentives

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***Abstract*— This paper works on the scheduling of smart household's controllable appliance in Demand Response environment. A smart residential electricity customer requires intelligent Home Energy Management System (HEMS) having the capability to shift and control the controllable appliance's consumption according to their preferences and economy. In this paper, an intelligent HEMS algorithm is proposed for optimal scheduling of household controllable appliances. The optimization problem minimizes the customer energy and reliability cost. Modelling results of two case studies show the effectiveness of proposed HEMS algorithm considering Time of Use (TOU) pricing scheme and incentives. Modelling of electric vehicle (EV), electric water heater (EWH) and air conditioner (AC) is done in this paper since they are controllable in nature. This HEMS system also considers the installation of PV panel with energy storage system (ESS), household loads, PV generation forecast and built-in characteristics of controllable appliances. By analyzing the results it can be observed that the daily energy consumption cost reduces in optimization-based approach up to 45.4 % compared with the rule-based approach.**

Keywords—Demand Response, Incentive-based demand response, Home Energy Management System, controllable loads, Time of use.

I. INTRODUCTION

Two decades back, heavy AT&C losses and energy crisis in India lead to adopting privatization of electricity distribution in some states. Now a day's continuous increment in the utilisation of renewable energy sources which are the intermittent source of energy creates uncertainty in the grid can be tackled by demand response (DR) by shifting the electric appliance load curve in the off-peak period [1]. To deal with such crisis Indian Govt. is making efforts to adopt smart grid technology and started providing smart meters in affordable price [2] with a target to produce energy of 175 GW till 2022 from renewable sources[3]. Smart Meters information transmission technology can help in reducing emission, aiding in sustainable energy supply and continuous updating the energy consumption and monitoring through real-time data transfer between customer and retailer thereby customer participates in demand response program [4]. Among various obstruction in successful execution of demand response program, lacking of robust advanced metering infrastructure (AMI) is the first one and after getting rid of it we have the second one i.e. customer's limitation to respond and for the effective automatic response a rule-based or an optimisation-based management system is the only solution and termed as home energy management system (HEMS) [5]. By considering the tariff structure, appliances value of lost load and appliance operational constraints a HEMS performs well in optimal scheduling and controlling the appliances in DR environment. Simultaneously, it can supply the surplus energy either grid or home if the source of distributed generation is available and thus a customer indirectly participates in ancillary services. [6]. The relentless effort has been made in smart grid technology to overcome the obstruction and to involve the customer and other entities in DR program. India also witnessed the same and the initiatives were taken by Delhi based electricity distribution utility, Tata Power Delhi Distribution Limited (TPDDL) has come up with advance metering infrastructure (AMI) based automated demand response (DR) program which is a part of smart grid journey [7]. This intelligent algorithm can be embedded in smart meter's load control unit and automated decision-making system [8].

II. MATHEMATICAL MODEL

Minimizing the electricity consumption bill of the customer is the main objective of this paper without violating the comfortability and maximum load allowed which requires an optimal decision by either aggregator or customer itself for scheduling [9], but inadequacy of resources and customer's decision-making limitation is the main hindrance in successful operation so the solution is an intelligent HEMS that schedules the electrical appliances without much active involvement of customer, only it requires certain inputs like temperature ranges of water heater, room temperature a customer wants, arrival and departure time associated with state of the charge and built in characteristics of household's controllable appliances that are made controllable through HEMS. Simultaneously HEMS can supply the surplus of household's energy resources like EVs, ESS and PV either to the grid or home depends on the cost minimization by taking care of our preferences and comfortability. It is observed that intelligent HEMS provides the facility to operate the electric vehicle in V2H and V2G mode [10]. This optimisation model includes EV, AC and EWH considering TOU pricing scheme and incentives where the customer pays for peak demand that may occur in cheaper price period that causes congestion which has been overlooked in the survey of the literature. Consumption scheduling of controllable household appliances and decisions for supplying the surplus energy either to the grid or home are the main advantage of the proposed optimization-based HEMS. The main objective of this paper is to illustrate the operation of HEMS and the optimal consumption scheduling while implementing DR programs. A rule-based approach HEMS is also implemented for the verification of the effectiveness of intelligent HEMS algorithm. The proposed HEMS model performed under TOU price- or incentive-based DR programs can be seen as an alternative to DLC programs. The net cost in rupees of electricity consumption and selling under TOU pricing scheme and incentives can be described as follows [11].

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$$\text{Cost}_{\text{TOU}} = \sum_{k\in K}(C^k . \sum_{t\in \Omega^k} P_t^{buy} . \tau) - \sum_{t\in T} P_t^{sell} . \tau . \pi_t^{sell} - \sum_{h\in H} DR_h . FI_h + E_d . \pi^{DPT} . \quad (1)$$

Where C^k is TOU tariff for category k. P_t^{buy} is power purchase from the grid during time interval τ. A customer can sell (P_t^{sell}) the surplus to the grid also with a price π_t^{sell} and the third term is revenue from participating in Demand Response program, DR_h indicates the difference between baseline load and actual load at incentive-based demand response hour and FI_h indicates the incentive or penalty both thus a customer pays penalty if actual load is greater than baseline load during demand response hour and the last term is for preventing the HEMS to attained the operation with peak demand (E_d) during cheaper period and refrain the power system network from congestion in off peak or cheaper price hour. Where π^{DPT} denotes the network tariff (₹/kWh) based on daily power purchase.

Subjected to the following constraints that enforce hourly power purchase from the grid is always less than peak demand E_d and power purchase during each time interval is also less than the maximum demand of from grid (P^{Max}).

$$\sum_{t\in \Omega^h} \tau . P_t^{buy} \leq E_d , \forall_h . \quad (2)$$

$$P_t^{buy} \leq P_t^{Max} , \forall_t . \quad (3)$$

The expression of power purchase and selling is described as follows:

$$P_t^{buy} = I_t^{inf} + P_t^{EWH} + p_t^{AC} + \sum_{\forall EV\in \Omega^{EV}} \left(P_t^{EV,ch} - P_t^{EV,home} \right) + \sum_{\forall ESS\in \Omega^{ESS}} \left(P_t^{ESS,ch} - P_t^{ESS,home} \right) - P_t^{PV,home} ; \forall_t . \quad (4)$$

Where P_t^{buy} and P_t^{sell} is the power purchase and sell in kW from and to the grid respectively, power purchase can be express as the power consumption by the firm load (I_t^{inf}), water heater (P_t^{EWH}), air conditioner (p_t^{AC}), charging of electric vehicle ($P_t^{EV,ch}$), charging of storage system ($P_t^{ESS,ch}$) and subtraction of the local production and supply to home, like PV power supply to Home ($P_t^{PV,home}$), storage system power supply to home ($P_t^{ESS,home}$) and electric vehicle power supply to home ($P_t^{EV,home}$). Selling power to the grid can be expressed as follows:

$$P_t^{sell} = \sum_{\forall ESS\in \Omega^{ESS}} P_t^{ESS,sell} + \sum_{\forall EV\in \Omega^{EV}} P_t^{EV,sell} + P_t^{PV,sell} ; \forall_t . \quad (5)$$

Where $P_t^{ESS,sell}$, $P_t^{EV,sell}$ and $P_t^{PV,sell}$ is the selling power to the grid by electric vehicle, storage system, and PV production respectively. Sometimes DR program comes with incentives for a specific hour, during the period HEMS helps in power consumption below baseline load ($I_h^{baseline}$) and thus benefitted the customer by reducing the cost.

$$DR_h = I_h^{baseline} - \sum_{t\in \Omega^h} \tau . P_t^{buy} , \forall h \in \Omega^{DR} . \quad (6)$$

A. EV and ESS Operational Constraints

HEMS enforces the operational constraints on electric vehicle (EV) and energy storage system (ESS) for successful operation and thus enhancing the life of the battery, where charging (P_t^{Ch}) and discharging power (P_t^{Dch}) of EV and ESS both remains under its ratings (P_{Max}^{Ch}). HEMS also takes care of the state of the charge (SoC) that should vary between maximum ($\text{SoC}_{Max}^{\text{EV}}$) and minimum ($\text{SoC}_{Min}^{\text{EV}}$) ranges. It has been assumed that EV charging takes place at home only. Since EV and ESS both contain the battery so having same operation constraints [11]. The charging status of EV (s_t^{Ch}) and ESS (s_t^{Ch}) will be 1 during the charging period and 0 if not being charged, the same status can be considered while in discharge mode. Operational constraints of EV is as follows:

$$0 \leq P_t^{Ch} \leq P_{Max}^{Ch} . s_t^{Ch} ; \forall_{EV} \in \Omega^{EV} , \forall_t \in T^{EV} . \quad (7)$$

$$0 \leq P_t^{Dch} \leq P_{Max}^{Dch} . s_t^{Dch} ; \forall_{EV} \in \Omega^{EV} , \forall_t \in T^{EV} . \quad (8)$$

$$\text{SoC}_{Min}^{\text{EV}} \leq \text{SoC}_t^{\text{EV}} \leq \text{SoC}_{Max}^{\text{EV}} . \quad (9)$$

The state of the charge of electric vehicle (SoC_t^{EV}) and energy storage system ($\text{SoC}_t^{\text{ESS}}$) updates according to the equation (10) and (11) but only electric vehicle's equation is shown due to space constraints. For ESS operational constraints in details [11] can be referred. The following expression of EVs SoC can be used while charging in progress at home.

$$\text{SoC}_t^{\text{EV}} = \text{SoC}_0^{\text{EV}} + \tau . [\eta_{.ch}^{\text{EV}} . P_t^{\text{EV},Ch} - P_t^{\text{EV},Dch}] \quad (10)$$

$$\text{SoC}_t^{\text{EV}} = \text{SoC}_{t-1}^{\text{EV}} + \tau . [\eta_{.ch}^{EV} . P_t^{EV,Ch} - P_t^{EV,Dch}] \quad (11)$$

While discharging, the power of EV ($P_t^{EV,Dch}$) can be used to supply either to the grid ($P_t^{EV,sell}$) or home ($P_t^{EV,home}$) same can be done by ESS as well. Availing this felicity it can be said that EV is involved in V2H (vehicle to home) and V2G (vehicle to grid) activity. For that we shall use discharging efficiency of EV (η_{Dch}^{EV}) and ESS (η_{Dch}^{ESS}), the expression for EV is as follows:

$$P_t^{EV,Dch} . \eta_{Dch}^{EV} = P_t^{EV,sell} + P_t^{EV,home} \quad (12)$$

We shall also avoid simultaneous charge and discharge of EV and ESS by following constraints. The expression for EV is as follows:

$$s_t^{EV,Ch} + s_t^{EV,Dch} \leq 1 \quad (13)$$

EV after charging up to the desired level go for the trip so few additional constraints are applicable to EV only which states that during the trip it will not be charged or discharge and at the time of departure state of charge should be up to the desired amount (SoC_d^{EV}).

$$s_t^{EV,Ch} + s_t^{EV,Dch} = 0 \quad (14)$$

$$\text{SoC}_t^{\text{EV}} = \text{SoC}_d^{\text{EV}} \quad (15)$$

B. AC Operational Constraints

AC in operating condition consumes power with its rating (Q_{AC}) and in off mode no power consumes and can operate with the maximum (T_{Room}^{Max}) and minimum (T_{Room}^{Min}) range of room temperature. The expression of room temperature and power consumption can be expressed as follows [12]:

$$T_{room}^{i+1} = \in_{air} . T_{room}^{i} + (1 - \in_{air}).\left(\mathrm{T}_{t}^{a} - \eta_{AC}.\frac{p_{t}^{AC}}{K_{air}}\right) \quad (16)$$

$$p_{t}^{AC} = s_{t}^{AC}.Q_{AC} \quad (17)$$

Where s_{t}^{AC} is the status of AC either on ($s_{t}^{AC} = 1$) or off ($s_{t}^{AC} = 0$), room temperature in degree Celsius at any interval (T_{room}^{i}) depends on the factor of inertia ($\in_{air}$) of air, ambient temperature (T_{t}^{a}), coefficient of performance (η_{AC}) and thermal conductivity (K_{air}) of air.

C. EWH Operational Constraints

EWH is a thermal storage device and a good candidate for demand response (DR) this paper using an expression of EWH for its modelling. After the assumption that inlet water temperature in EWH is equal to the ambient temperature, the model can be described as follows [11]:

$$\mathrm{T}_{t}^{EWH} = \mathrm{T}_{t}^{a} + R.P_{t}^{EWH} - \left(\frac{M - m_{t}}{M}\right)(\mathrm{T}_{t}^{a} - \mathrm{T}_{t-1}^{EWH})exp^{\left(-\frac{\tau}{R.C}\right)}, \quad \forall_{t} \in \mathrm{T}. \quad (18)$$

The temperature of EWH (T_{t}^{EWH}) depends on ambient temperature (T_{t}^{a}), thermal resistance (R), power consumption (P_{t}^{EWH}) in kW, the capacity of the water tank (M) in the litre, hot water usage hourly (m_{t}) and thermal capacitance (c). EWH operates with two status either on ($s_{t}^{EWH} = 1$) or off ($s_{t}^{EWH} = 0$). Power capacity of EWH is denoted as Q.

$$P_{t}^{EWH} = Q.s_{t}^{EWH}, \forall_{t}. \quad (19)$$

Temperature of hot water vary from minimum ($\mathrm{T}_{low,t}^{EWH}$) to maximum ($\mathrm{T}_{up,t}^{EWH}$)

D. Rule-based HEMS

A rule-based approach is used for comparing the effectiveness of intelligent HEMS algorithm, so we treat it as a benchmark algorithm for scheduling of EV, EWH and AC. The scheduling algorithm of EV and EWH is discussed by M. A. F. Ghazvini et al. [11] and for AC the benchmark algorithm for scheduling is developed in this paper. Whereas AC stops consuming power when the temperature is below the lower limit (T_{Room}^{Min}) or power consumption of household is greater than maximum limit ($\mathrm{P}^{\mathrm{Max}}$) as mentioned in algorithm 1.

In the rule-based approach, the PV generation surplus after consuming in the household appliances is sold to the grid. The main constraints here is not to violate the minimum temperature of the room in case if AC and to follow the specific range of SoC in case of EV along with the maximum power consumption. The algorithm of EV used in [11] is a heuristics algorithm for EVs charging which follows the first come and first charge concept and again constraints here is not to violate the household's power limit.

Algorithm 1. Scheduling of AC

for t = 1 to n (T)
  If $T_{room}^{i} \geq T_{Room}^{Min}$
    $s_{t}^{AC} \leftarrow 1$
    $p_{t}^{AC} \leftarrow s_{t}^{AC}.Q_{AC}$
  end if
find T_{room}^{i+1} from (16)
x ← $load_{t} + p_{t}^{AC}$
If x > $\mathrm{P}^{\mathrm{Max}}$ **then**
$s_{t}^{AC} \leftarrow 0$
$load_{t} \leftarrow load_{t} + p_{t}^{AC}$
find p_{t}^{AC} from (17)

II. Test System

Expected PV production of 4 kW solar panel shown in fig. 2 and ambient temperature throughout a day shown in Figs. 5 and 6 respectively, provided by National Renewable Energy Laboratory (NREL) [13] for the load scheduling and comparing the effectiveness of the proposed algorithm. Firm load data shown in figure 2 have been taken for a house contracted with 17.25 kVA of permissible supply from PSACE IEEE PES [14]. It has been taken care that scheduling horizon starts at 09:00 AM because of EVs arrival and departure can be simulated with our daily routine. The time slots for optimization is done for every 5 min and thus for the 24 hr time period there will be 288 slots for optimization by considering the expected pricing scheme provided by TPDDL for the fiscal year (2017-18) which usage two price in a day, one for peak hours and 2nd for off-peak hours with a rebate of 35% in off-peak hours [15] as shown in fig 1. In this paper peak hour's price is taken as 5 ₹/kWh and for a better framework of incentives table I considers a random data for incentives and penalty provided to customer depends on whether customer consume power less than or more than baseline load, but a customer sells the surplus to grid with a constant price of 3.7 ₹/kWh which is 90% of the average buying price of electricity. The household comprising controllable loads which are EVs, AC and EWH. After receiving incentives for a specific hour in demand response (DR) environment it can be said that customer is involved in incentive-based DR (IBDR) program. In order to show the effectiveness of the proposed HEMS algorithm entire work has been divided into two case studies, first one is the rule-based approach and the second one is the optimisation-based approach.

TABLE I: INCENTIVE PLANS

Hours	Plans for incentive-based DR program	
	Baseline load (kWh)	***Incentive/Penalty (₹/kWh)***
14:00	6	1.6
20:00	4	1.34
21:00	4.5	1.39
0:00	7	1.2
7:00	4	1.4
8:00	4.5	1.53

A TOU tariff structure contains the different price for specific hour provided by distribution utility for the participating customer and during the incentive hour HEMS influences the power consumption of household appliances and thus reducing the cost of power purchase from the grid. The present paper works on cost reduction considering TOU price with incentives by incorporating EV, AC and EWH as a controllable appliance in HEMS, which is the main contribution of this paper.

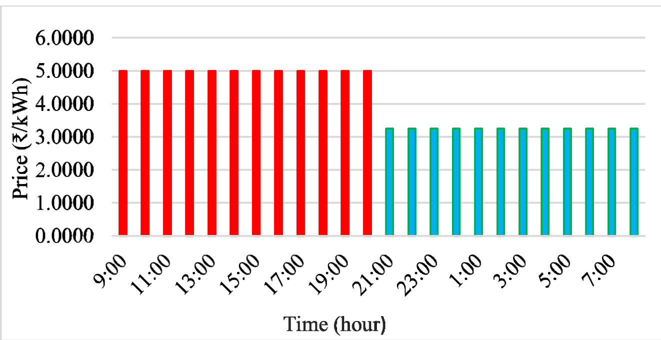

Fig.1. TOU tariff structure

Built-in characteristics of EVs and ESS is shown in table II, which gives the details of capacity, the rate of charge and discharge, arrival and departure time with desired SoC of EVs. Where some inputs are required to update on the daily basis.

TABLE II**:** BUILT- IN CHARACTERISTICS OF EVS AND ESS

Built-in characteristics & Expected SoC	EV1	EV2	ESS
Brand	Mahindra Rewa	Chevrolet volt	-
Capacity (kWh)	10	16.5	46
Charge rate (kW/h)	2	3.3	4.5
Discharge rate (kW/h)	1.739	2.805	3.8
Charging efficiency	0.87	0.89	0.86
Discharging efficiency	0.9	0.91	0.85
Arrival time	9:30	16:30	-
Departure time	20:45	7:30	-
% SoC at Arrival time	16	20	-
% SoC at Departure time	89	90	-

TABLE III: BUILT- IN CHARACTERISTICS OF AC AND EWH

AC		EWH	
Factor of inertia	0.95	Thermal capacitance (kWh/^{0}C)	863.4
Coefficient of performance	2.5	Water Capacity (L)	400
Capacity (kW)	2.352	Capacity (kW)	4.5
Thermal conductivity (kW/^{0}C)	0.0145	Thermal Resistance (^{0}C/kW)	1.52

They are expected arrival and departure time associated with its state of the charge in terms of percentage. Built-in characteristics of EWH and AC has shown in table III, are the necessary requirement for HEMS modelling. It also requires the forecast of daily water consumption shown in fig. 3.

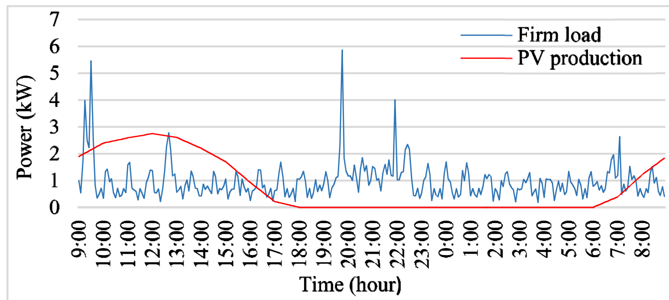

Fig.2. Firm load and ambient temperature

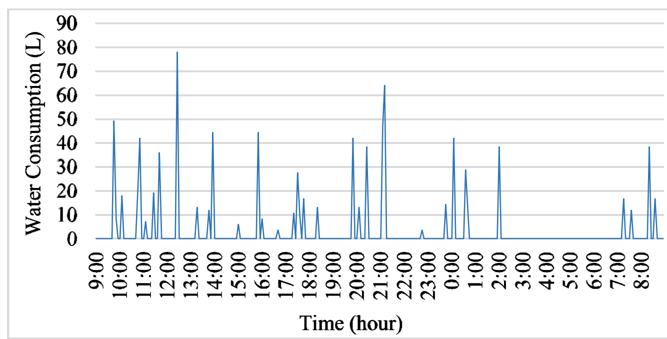

Fig.3. Water Consumption

III. RESULTS

Development of HEMS model has been done as mixed integer linear programming (MILP) problem where some of the variables are constrained to be integers and rest are non-integers. Modelling of MILP problem is done in GAMS 23.8.2 by using a commercial solver CPLEX 12 [16]. Time taken for solving the optimisation model is few secs. with no of iteration 3462 in a computer having Windows 10, 8 GB of RAM and 2.3 GHz processor. Table IV contains the result of rule-based approach in first case and optimisation-based in the second case . it can be observed the cost reduces 45.4% by using optimization-based approach. By using the intelligent algorithm in case 2 where variation in room temperature allowed in the range of 18 ^{0}C to 24 ^{0}C with initial 21^{0}C shown in fig. 9, the range of room temperature remains wide without violating the comfortability of the customer as compared to case 1 which deals with the rule-based approach as shown in fig. 5 where the same range allowed. In case of EWH temperature range by using intelligent algorithm allowed 45^{0}C to 55^{0}C with initial temperature 50^{0}C as shown in fig. 10 and in rule-based approach with same range hot water temperature remains in between 47.943^{0}C to 54.998^{0}C with the same initial temperature 50^{0}C as shown in fig. 6. From the observation, it is clear that in rule-based approach water temperature remains above 53.5^{0}C for most of the time on the other hand in optimization-based approach temperature remains below 47^{0}C for most of the time. By using an intelligent algorithm it is observed that the temperature range varies according to the preference, comfortable range and economy. In electric vehicle's scheduling by using rule-based approach where EV is charged without any interruption means no involvement in selling or controlling of charge shown in fig. 4, while in optimization-based approach in fig. 8, EV supplies power either to grid or home and respond the incentives also along with controlling in the rate of charge, thereby power consumption during the hour of incentives remains minimum and customer get benefits. It can be clearly seen that the power purchase from the grid as shown in fig. 11 which is governed intelligent algorithm is minimum when the signal of peak price and incentives is received thus cost reduces which is not same in fig. 7 of case 1 which is governed by the rule-based approach.

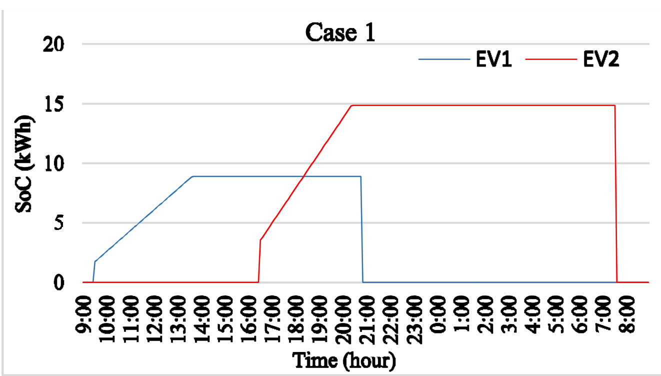

Fig.4. SoC of EVs during scheduling horizon

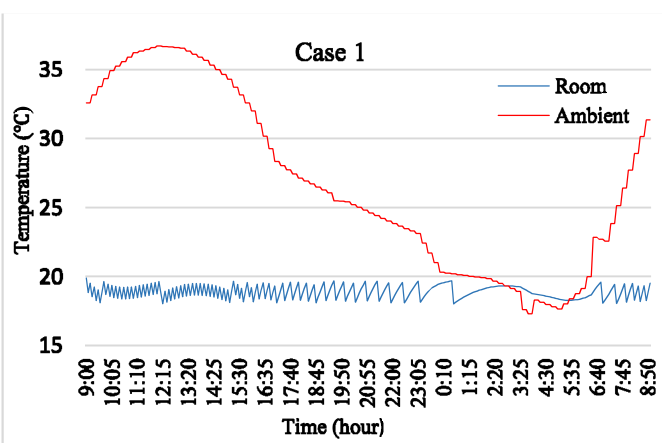

Fig.5. Room temperature and ambient temperature

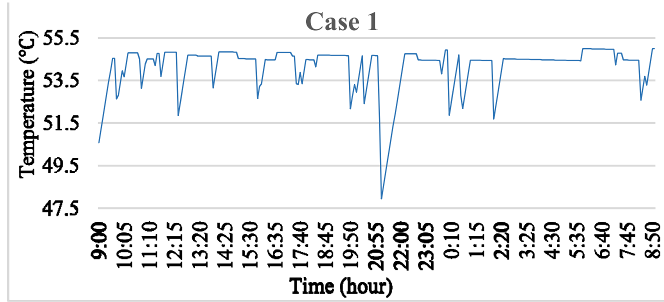

Fig.6. Hot water temperature

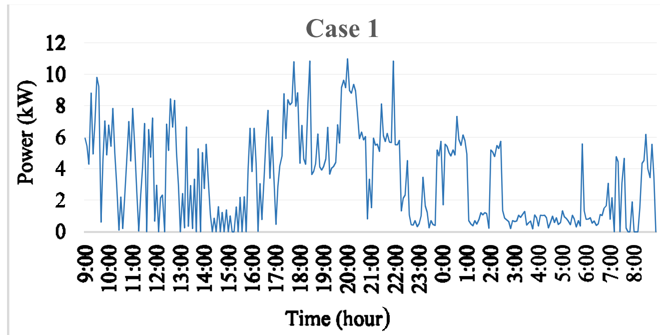

Fig.7. Power purchase from Grid

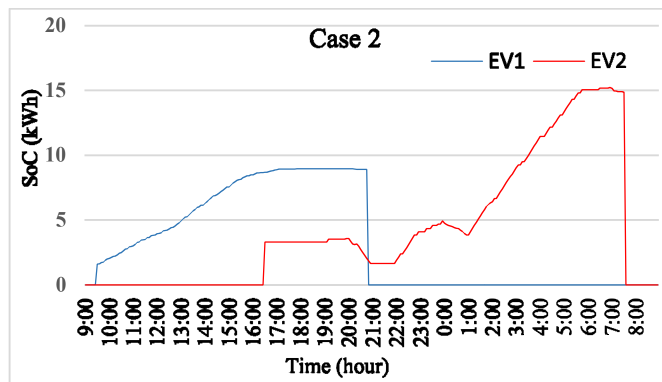

Fig.8. SoC of EVs during scheduling horizon

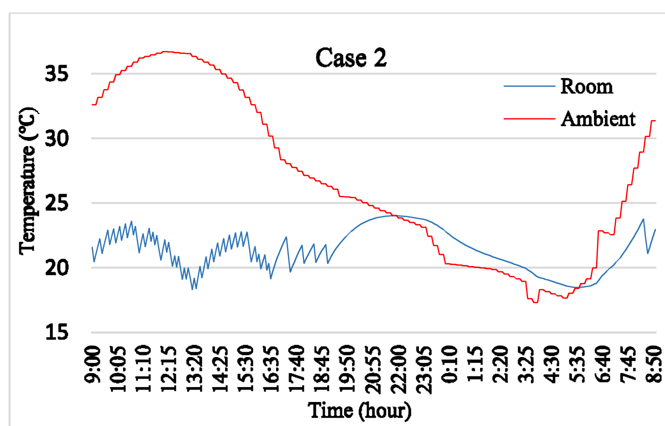

Fig.9. Room temperature and ambient temperature

TABLE IV: OUTCOMES OF CASE STUDIES

Cost/Consumption	Case 1	Case 2
Cost (₹)	353.81	192.94
Energy consume by EWH (kWh)	41.25	24.75
Energy consume by AC (kWh)	13.328	8.82

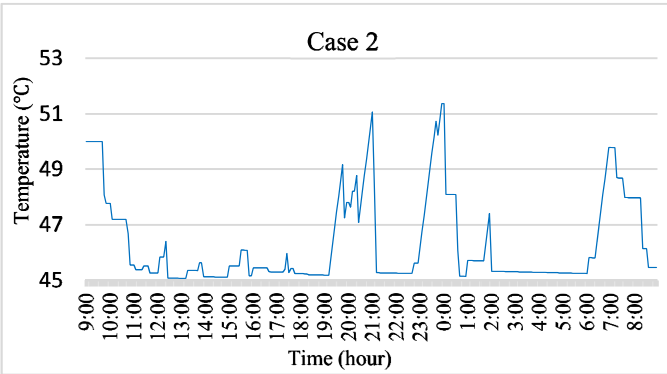

Fig.10. Hot water temperature

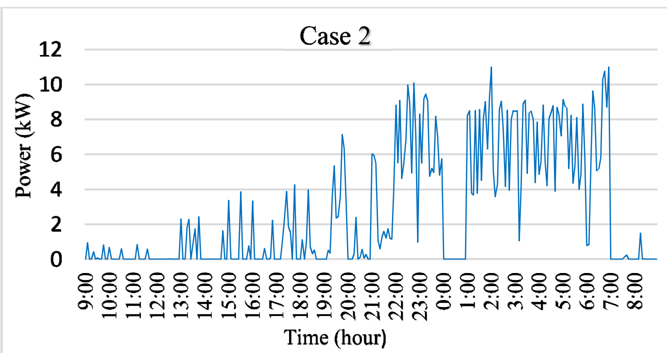

Fig.11. Power purchase from the Grid

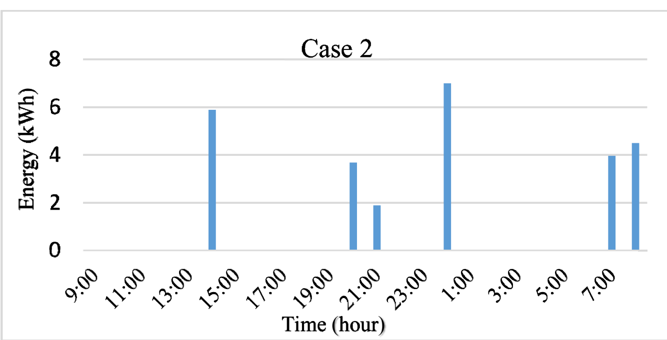

Fig.12. Difference between baseline load and actual consumption

IV. CONCLUSION

An intelligent algorithm has been proposed in this paper for scheduling the controllable appliances like EVs, AC and EWH integrating ESS with PV panel considering a tariff structure TOU for a house that participates in demand response program and for the effectiveness of the scheduling a comparing tool is used called rule-based approach. With the help of the main idea of this paper, future work can be done on power quality, adding the more controllable device, making HEMS system more robust. Future work can also be done on the congestion management.

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