Home Energy Management Incorporating PV and Energy Storagewith Utility under Demand Response

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Abstract

Renewable energy sources (RESs) and energy storage systems (ESSs) are important for an energy management system (EMS). An algorithm is proposed for home energy management (HEM) using energy storage systems (ESSs) and distributed generation (DG). ESSs are considered plug-in hy- brid electric vehicles (PHEV) and uninterrupted power supply (UPS), whereas DG is a solar pho- tovoltaic (PV) system. These are incorporated in the scheduling of a house load with utility supply under demand response (DR). The Loads are taken from different varieties such as heating, venti- lating, and air conditioning (HVAC), electric water pump (EWP), and electric water heater (EWH). The scheduling methods are normal ON-OFF and smart particle swarm optimization (PSO) meth- ods. The algorithm is designed in MATLAB environment for electricity bill reduction of a house under different conditions for end-user comfort. Where, the energy storage and PV system are incorporated into the utility supply through charging-discharging and PV generation conditions, respectively. We have also considered the curtailment duration in the scheduling algorithm in both methods.

Keywords: Demand Side Management (DSM), Demand Response (DR), Real-Time Pricing (RTP), Particle Swarm Optimization (PSO)

1. Introduction

Demand-side resources (DSRs) are the base of demand-side management (DSM). Thus, DSM is scheduling of DSRs for an energy management system. It covers all concepts and methods for energy management on the demand side. The resources have a large number of varieties among energy sources, energy storage, and loads under demand response (DR) and tools of optimization in a smart grid era [1]. House resources have a wide scope for home energy management (HEM), building energy management (BEM), and distribution system energy management (DSEM) [2, 3]. HEM provides the best platform for optimal use of these resources. Hence, it requires a proper algorithm for scheduling of available resources.

There are many previous research papers that describe the resource availability on the de- mand side [1]. These resources can be scheduled for HEM as described in [2]. Many articles are adopting using different types of techniques and methods for energy management of a house. Paper [3] proves that the total load consumption of a house can be reduced at a certain level by priority-based load scheduling. Scheduling of interruptible loads (ILs) provides a potential to DSRs in terms of system security and capability [4]. Here, it is described as the scheduling of hourly interruptible loads in a time frame using binary particle swarm optimization (BPSO). It converts multiobjective optimization problems to a single aggregated objective function. In [2], DSRs have been scheduled for the BEM system by particle swarm optimization (PSO). Reference

[5] develops an evolutionary algorithm for solving the smart grid technique for cost minimization and load reduction. Similarly in [6], the use of the time-of-day (TOD) tariff is studied for resi- dential consumers in the distribution system of an educational institute in the view of the Indian power sector. Price controlled home energy management is discussed in [7]. Here, household appliances are optimally scheduled for HEM under the day-ahead price. There are considered different types of devices as water heaters and air conditioners for thermostatic, dishwasher and washing machines for non-thermostatic and electric vehicles (EVs) for distributed generation and energy storage systems (ESSs) [8]. Where two types of scheduling problems are considered as energy generation and consumption in the presence of various resources.

A solar photovoltaic (PV) system is the most useful and available renewable energy source (RES) in terms of energy generation for HEM [9]. A wide range of research articles is available regarding the scheduling of PV energy generation. Article [10] provides PV generation sharing networks for local consumers in day-ahead scenario. Power management and control scheme is explained in the hybrid PV system with AC-DC supply [11]. Control and planning in real-time through stochastic optimization with integration of PV and storage system is validated experimen- tally in [12]. In the research article [13], the usage of diesel generators has been reduced with the help of renewable energy resources (PV system) and battery energy management system. Simi- larly, in [14], the cost of operation for EV charging at energy stations is reduced by the integrationof PV and storage systems.

Thus, ESSs play important roles for energy management providing a solution for intermedi- ate PV generation characteristics by facilitating a flexible use of the generation [15]. The charging and discharging of batteries are evaluated by incorporating utility and RESs for balancing the supply-demand in real-time [16]. Another article [17] shows the opportunities of ESSs for cost minimization of house electricity consumption with RESs and smart grid integration. Whereas, in [18], hybrid electrical energy systems are analyzed and proved that these systems are profitable for electricity bill reduction of a house. Three types of control strategies related to energy storage, task specified, and heating devices are adapted for cost minimization in a home energy manage- ment system (HEMS)[19]. Reference [20] includes various operating modes of plug-in electric vehicle (PEV) for cost reduction in smart HEMS. Costs of energy and thermal discomfort of heat- ing, ventilating, and air conditioning (HVAC) system are investigated with the charging of energy storage and EV systems in a smart home [21]. Scheduling of PV systems is provided consider- ing the interest of the consumer and utility operators [22]. This is a multiobjective problem for economically charging and maintaining the load profile.

Demand response also plays an important role in energy management. In article [3], the potential of DR for HEM in electricity market is described. In internet of things (IoT), HEMSs are useful for balancing supply and demand through metaheuristic optimization and DR [23].

Thus, a lot of articles are available on demand-side resources and their scheduling for energy management.

However, in the previous articles, there are not developed a novel algorithm for home energy management considering different conditions. The main contributions of this article are as follows.

1. A novel algorithm is developed for the incorporation of energy storage and PV system with scheduling of different types of a-house device for home energy management and electricity bill reduction.
2. The incorporation and scheduling are carried out by the normal ON-OFF and smart methods under demand response and different conditions. For the smart method, PSO algorithm is considered.
3. The different conditions considered in the scheduling are as follows:
    - End-user comfort,
    - Curtailment,
    - Charging-discharging of batteries with maintaining SOC level before plug-out or cur-tailment,
    - Utility supply at real-time price,
    - DG generation, and
    - Load characteristics.
4. Different classes of house devices are included for the scheduling in the algorithm as follows:
    - *Loads*: Heating ventilating and air-conditioning (HVAC), electric water heater (EWH), and electric water pump (EWP) are loads of a house, which are functions of energy consumption. The functions of HVAC and EWH have been controlled according to the user comfort temperature without violation of a set of constraints. Whereas, EWP is taken as the shiftable load. HVAC, EWH, and EWP are the major energy-consuming devices.
    - *Energy Storage Systems*: Plug-in hybrid electric vehicles (PHEV) and uninterrupted power supply (UPS) are considered as energy storage devices. These devices work as loads as well as sources of energy.
    - *DG System*: Solar photovoltaic renewable energy source is considered as distributed generation (DG) for local power supply to house loads.

5. The energy storage and PV system are incorporated with utility for a flexible power supplyto the house loads. The incorporation is studied in different cases.
6. The case studies are compared and analyzed by both the normal ON-OFF and smart methods through consumption and cost reduction.
7. The proposed algorithm provides scheduling in such a way to manage energy in differenttime slots of 15-minutes according to the conditions.
8. It is a simple and realistic scheduling algorithm for house devices in MATLAB environment,which has a scope of implementation for a large number of houses.

Thus, the proposed algorithm is very useful in a realistic world. To the best of our knowledge, this type of scheduling algorithm has not been considered in the previous research articles.

The rest of this article is organized in the following sections. Section II explains the basics of demand-side management, whereas Section III provides the detail on load models. Section IV describes the proposed algorithm. Results are discussed in Section V. Section VI concludes the paper.

2. Demand Side Management

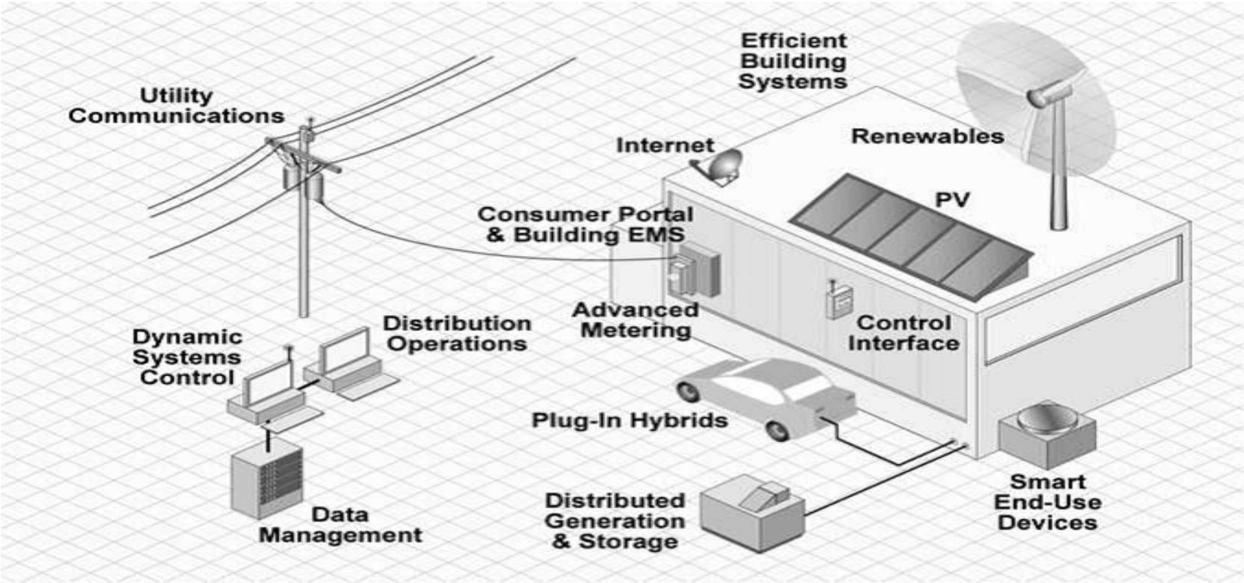
Demand-side management has a whole range of energy management in a distribution system. California of United States is the origin of DSM concept. All DSM works that have been done in the US strove to overcome financial barriers, provide financial incentives, offer suitable prod- ucts in the electricity market, and present sufficient information to help consumers shifting their purchasing decisions. However, the responsibility of DSM implementation was heavily placed on the utility sector and the mechanism has failed to form natural market incentives for sustainable demand-side energy efficiency improvement. Moreover, the utility-based DSM mechanism also shows its limitation in engaging active end-user participation.

As electric sector competition is introduced, the fate of utility-administered DSM has changed. A new mechanism for a competitive electricity market is under development in worlds countries. The recent development of public benefits funds and market transformation-based efficiency pro- grams, and the new roles of utilities, ESCOs, and public or non-profit energy efficiency institutions

may play an important role in a possible future direction for the design of DSM policies in many issues such as interruptible loads.

To understand the demand patterns and effects of various DSM technologies and policy strategies on demand and further properly manage the demand, an analytical tool must be devel- oped to utilize the limited information on consumption available to identify robust DSM options. To perform the quality of DSM research, as well as other related electricity sector research on both supply and demand-side planning such as integrated resource planning (IRP), the researchers also require detailed information on the composition and dynamics of electricity demand. Particularly, a basic understanding of peak loads, as to when and how they have occurred, their variations by socio-economic factors, and how they may change in the future are among the most important requirements.

Fig. 1: A home energy management resources [24].



2.1. A Home Energy Management Resources

A housing resource for energy management may vary or be affected by many factors such as social and political awareness, economic and environmental conditions, etc. However, a smart home is equipped as shown in Fig. 1 with the internet of things, renewable energy sources, en- ergy storage, smart end-use devices, dynamic systems control, data management, integration with utility power, smart metering consumer portal, etc., [1].

In this research article, we have considered the following resources for optimal scheduling.

2.1.1. Demand Response

Demand response is a concept or technique of DSM under smart grid which provides op- portunities to end-users for participating in the electricity market for energy management. The demand response can be classified as follows in Fig. 2.

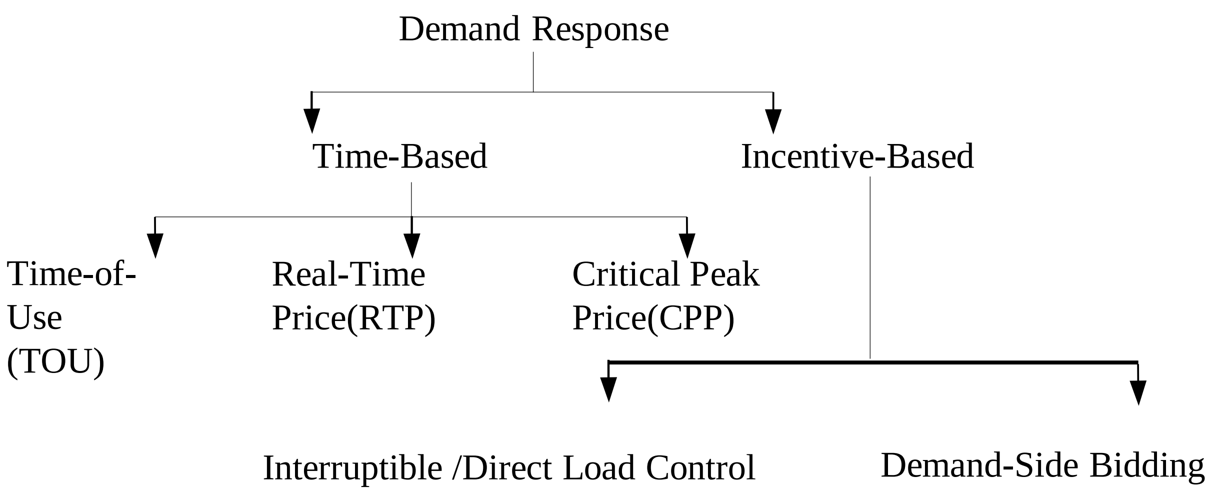


Fig. 2: Classification of demand response.

Here, real-time price of utility as shown in Fig. 3 has been considered for scheduling of a house devices.

2.1.2. Electric Devices

A house electric devices, that are used in the study are as follows: electric water pump (EWP), heating ventilating and air conditioning (HVAC) system, electric water heater (EWH), plug-in hybrid electric vehicle (PHEV), uninterrupted power supply (UPS), and solar photovoltaic

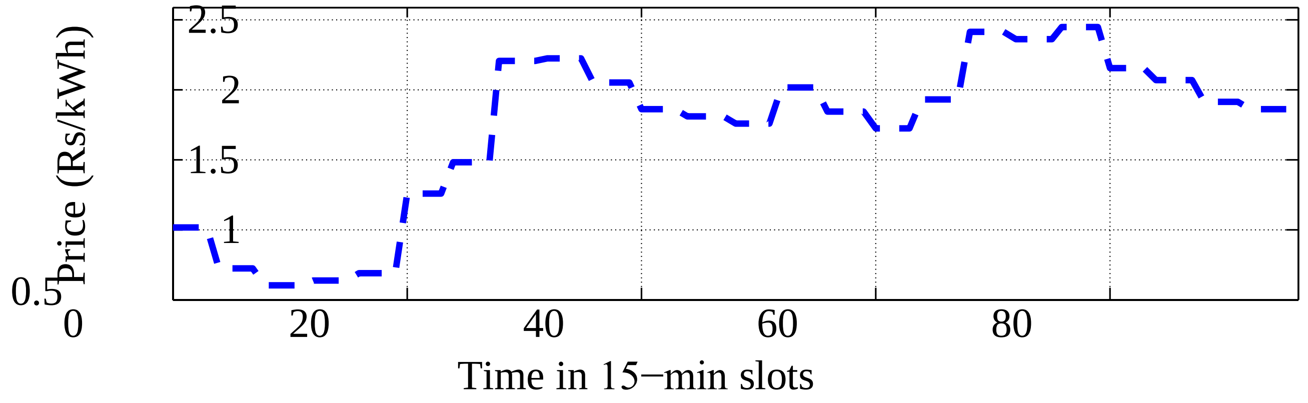


Fig. 3: Real-time price of utility [2].

(PV) system. With the help of these devices and energy services of utility, energy storage, and PVsystem, we can achieve the desired load shapes by implementing DR program.

2.2. *A Home Energy Management System*

”A home energy management system can be defined as a complete body of monitoring, analyzing, and controlling a set of available house resources for optimal scheduling in such a way the desired goal can be obtained.”

3. Load Models

In this article, the scheduling of mixed types of electric loads is studied, with the incorpo- ration of PV and energy storage systems with utility under demand response for home energy management and electricity bill reduction of a house. Hence, there is a requirement for models of devices that should be a function of energy. The models are as follows [2].

3.1. *Heating Ventilating and Air Conditioning*

In the heating, ventilating, and air conditioning systems, the required room temperature is the function of energy consumption as follows.

$$T_{ac}(t+1) = E \times T_{ac}(t) + (1 - E) \times \left[T_a(t) + (COP) \times \frac{q_{ac}(t)}{A} \right] \quad (1)$$

where,

$q_{ac}(t)$ is power consumption in t^{th} time slot (kW),

$T_{ac}(t)$ is indoor temperature in t^{th} time slot (°C), $T_a(t)$ is ambient temperature in t^{th} time slot (°C), A is equivalent conductivity (kW/°C),

E is system inertia,

COP is coefficient of performance.

3.2. Electric Water Heater

The water temperature of the electric water heater is a function of electric energy as in thefollowing model.

$$T_{wh}(t+1) = T_{wh}(t) \times \left(1 - \frac{f_o(t)}{v}\right) + T_{in}(t) \times \left(\frac{f_o(t)}{v}\right) + \left(1000 \times \frac{0.859}{60v}\right) \times \left(q_{wh}(t) - \frac{A}{R} \times (T_{wh}(t) - T_a(t))\right) \quad (2)$$

where,

f_o is hot water demand or consumption rate ($\frac{m^3}{hr}$),

v is volume of tank (m^3),

R is thermal resistance ($\frac{m^2\ {}^\circ C}{W}$),

A is area of the tank (m^2),

T_{wh} is temperature of hot water (°C), T_{in} is inlet water temperature (°C), T_a is ambient temperature (°C).

3.3. Electric Water Pump

Electric water pump is also a function of electric energy consumption as in the given model.

$$v_{wp}(t+1) = v_{wp}(t) + \left(\frac{\eta_m \times q_{wp}(t)}{H} - d(t)\right) \quad (3)$$

where,

d is water demand ($\frac{m^3}{hr}$),

v_{wp} is water level in tank (m^3),

$q_{wp}(t)$ is energy consumption in t^{th} time slot (kWh),

H is head of water level (m),

η_m is motor efficiency.

3.4. Electric Vehicle and UPS-Inverter

Electric vehicle and UPS systems use batteries. Hence, the modeling of charging and dis-charging of a battery is given as follows.

$$soc_{ev}(t+1) = \begin{cases} soc_{ev}(t) + \eta_{ev} \times q_{ev}(t), & \text{if charging} \\ soc_{ev}(t) - \dfrac{q_{ev}(t)}{\eta_{ev}}, & \text{if discharging} \end{cases} \quad (4)$$

where,

$soc_{ev}(t)$ is state of charge t^{th} time slot (kWh), $q_{ev}(t)$ is charging energy t^{th} time slot (kWh), η_{ev} is charging /discharging efficiency.

In the case of the UPS-Inverter, subscript *ev* is replaced by *inv*.

3.5. Photovoltaic System

A rooftop solar photovoltaic system is considered for a house of 2500 square feet area [3]. The rated capacity of PV system is 4.8 kWp. The daily average output of the PV system for winter is taken in Indian scenario as shown in Fig. 4 [25].

4. An Algorithm for Home Energy Management

Scheduling algorithm for house loads incorporating PV and energy storage systems with utility supply under demand response in time-slots of 15-minutes for a home energy management and electricity bill reduction of the house is given as follows.

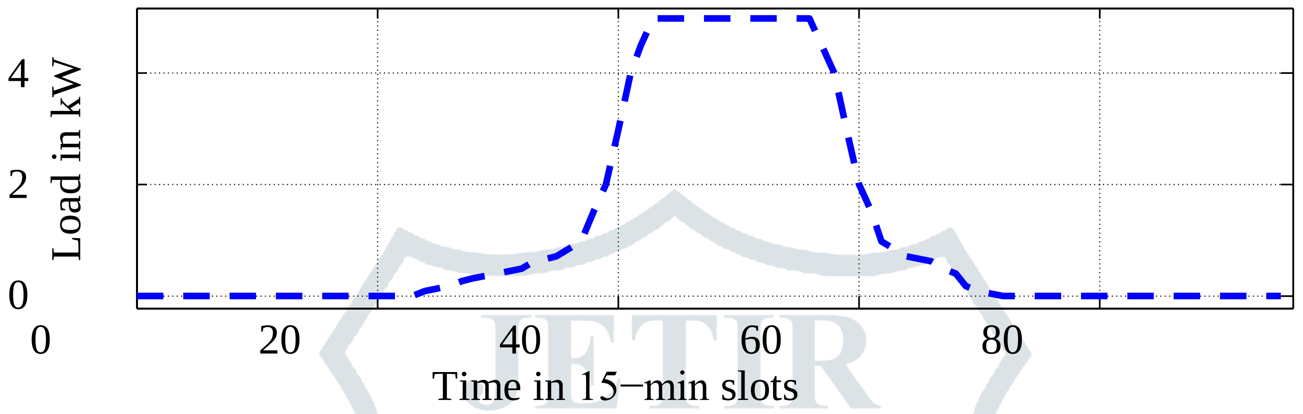


Fig. 4: Power output of a rooftop solar photovoltaic system.

4.1. Objective Function

The objective of the problem is to reduce the total cost of electricity for a typical house for aday. Therefore, the objective function to be minimized is

$$
\begin{aligned}
Fun = & \sum_{t=1}^{T} Pr(t) \times \left[q_{ac}(t) + q_{ewh}(t) + q_{ewp}(t) \right] \\
& + \sum_{t=1}^{T} Pr(t) \times \left[q_{ev}(t) + q_{inv}(t) \right] \\
& + \sum_{t=1}^{T} Pr_{pv} \times q_{pv}(t) \\
& + P_{1} \times \left(soc^{on}_{ev} - soc^{max}_{ev} \right) + L_{1} \times \left(soc^{off}_{ev} - soc^{max}_{ev} \right) \\
& + P_{2} \times \left(soc^{on}_{inv} - soc^{max}_{inv} \right) + L_{2} \times \left(soc^{off}_{inv} - soc^{max}_{inv} \right) \\
& + H_{1} \times \left(T^{t_1}_{wh} - T^{t_{96}}_{wh} \right) \\
& + H_{2} \times \left(v^{t_1}_{wp} - v^{t_{96}}_{wp} \right) \qquad (5)
\end{aligned}
$$

where,

T is number of time slots, t = 1...96,

Pr is price of utility supply, Pr_{pv} is price of

PV generations, q_{pv} is PV generations,

$P_1, P_2, L_1, L_2, H_1, H_2$ are penalties.

In this algorithm, a whole day is divided into 96 intervals of 15-minutes each. The first three summation terms calculate the costs of loads (HVAC, EWH, EWP), energy storage (PHEV, UPS), and PV system operations, while the last six terms are added for penalty factors.

4.2. Constraints

Constraints of this problem are as follows.

$$0 < q_{ac}(t) < q_{ac}^{max} \tag{6}$$

$$T_{ac}^{min} < T_{ac}(t) < T_{ac}^{max} \tag{7}$$

$$q_{ev}^{min} < q_{ev}(t) < q_{ev}^{max} \tag{8}$$

$$soc_{ev}^{min} < soc_{ev}(t) < soc_{ev}^{max} \tag{9}$$

$$q_{inv}^{min} < q_{inv}(t) < q_{inv}^{max} \tag{10}$$

$$soc_{inv}^{min} < soc_{inv}(t) < soc_{inv}^{max} \tag{11}$$

$$0 < q_{wh}(t) < q_{wh}^{max} \tag{12}$$

$$T_{wh}^{min} < T_{wh}(t) < T_{wh}^{max} \tag{13}$$

$$0 < q_{wp}(t) < q_{wp}^{max} \tag{14}$$

$$v_{wp}^{min} < v_{wp}(t) < v_{wp}^{max} \tag{15}$$

The system parameters are tabulated as in Table 1.

4.3. Particle Swarm Optimization

The following are the basic equations for particle swarm optimization (PSO) [2]. In eachiteration, the position of a particle is updated by its velocity as given in equations.

$$v_i(t+1) = w \times v_i(t) + c_1 \times r_1 \times \left(p_{best_i} - x_i(t)\right) + c_2 \times r_2 \times \left(g_{best} - x_i(t)\right)$$

$$x_i(t+1) = x_i(t) + v_i(t+1)$$

where,

p is number of particles,

Table 1: System Study Parameters[3][2]

Parameter	Value	Unit
HVAC		
A_{ac}	0.28	kW/ °C
E	0.93	p.u.
q	3.5	kW
COP	2.5	p.u.
Electric Water Heater		
R	3.17	$\left(\frac{m^2 \times {}^\circ C}{W}\right)$
A_{wh}	1.97	m^2
v	0.273	m^3
q_{ewh}	4.5	kW
f_o	[0 0.08]	$\frac{m^3}{hr}$
T_a	26	°C
Electric Water Pump		
v_{max}	2.5	m^3
v_{min}	0.5	m^3
q_{pump}	1.5	kW
η_m	0.85	p.u.
Electric Vehicle		
soc_{max}	50	kWh
soc_{min}	20	kWh
q_{ev}	5	kW
η_{ev}	0.85	p.u.
UPS-Inverter		
soc_{max}	25	kWh
soc_{min}	3	kWh
q_{inv}	5	kW
η_{inv}	0.85	p.u.
Solar Photovoltaic System		
House	2500	ft^2
q_{pv}	4.8	kWp

t is iterations number,

r_1, r_2 are random numbers between [0,1],

c_1, c_2 are acceleration constants,

w is inertial constant.

5. Results and Discussion

In this research article, demand response is the main part of the scheduling algorithm. Ac- cording to 15-minute optimal cost calculations by the scheduling of a house load (EWP, EWH, HVAC) with utility supply, PV generations, and charging-discharging of PHEV and UPS systems as well as consumer comfort for the temperature of HVAC and EWH, SOC levels of PHEV and UPS systems, and water level of the tank, These devices of the house is scheduled by normal ON-OFF and smart PSO methods as in following different cases.

5.1. *Case-I: Considering only Loads and Utility Supply with Curtailment*

In this case study, we have considered only energy-consuming devices such as EWP, EWH, and HVAC for scheduling. The scheduling is carried out by normal ON-OFF and smart PSO methods according to a set of constraints and real-time price (RTP).

Fig. 5 shows scheduling results of house loads when the loads are supplied only by the utility in a dynamic price environment. This scheduling algorithm includes interruptions between 48 to 60 slots of time.

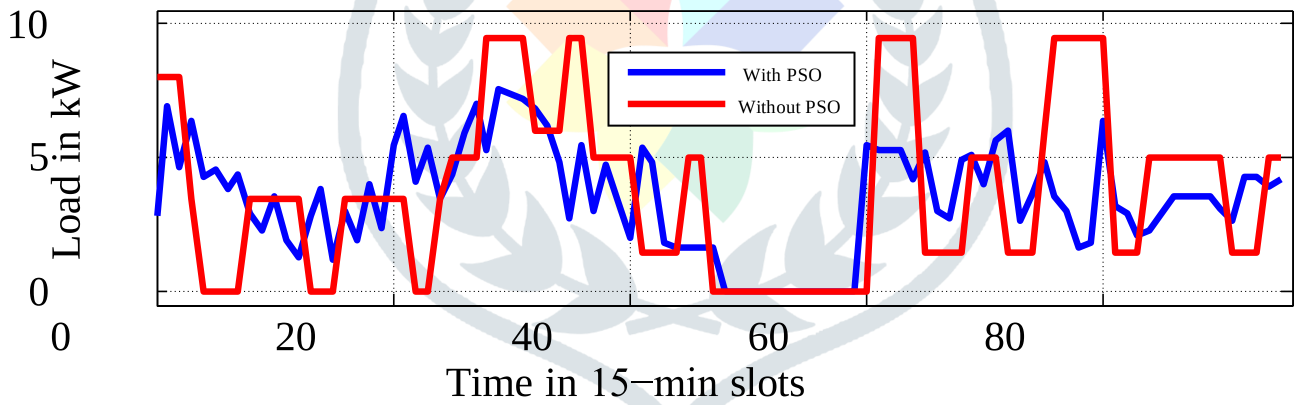


Fig. 5: Load profiles by normal ON-OFF and smart methods, when power supplied only by utility.

As shown, the maximum peak of the house load goes to about 9.5 kW in the normal ON- OFF method, whereas this is around 8 kW in the smart method due to the shifting of loads at different time slots. Normal ON-OFF scheduling load profile shows deep valleys and high peaks at low and higher prices, respectively. These peaks occur due to consumption requirements that are unable to shift the loads at that period for fulfillment of user comfort. In comparison to the normal method, the smart method clips the peaks and fills the valleys by load shifting at high and low prices, respectively, through optimal scheduling of the loads with minimum consumption andcost.

The total consumption and costs of the scheduled profiles are given in Table 2. The consump- tion with the normal ON-OFF method is 391.50 kWh, whereas with the smart method is 335.09 kWh. Hence, the reduction by the smart method is 56.40 kWh, which is 14.43 % of the normal ON-OFF method. Costs data of the energy consumption are also given in Table 2. Where the total energy consumption costs of a house are calculated by the two methods. The costs are Rs. 742.76 and 599.28 by normal ON-OFF and smart methods, respectively. Thus, the bill reduction of the house by the smart method is Rs. 143.48, which is 19.32 % less than the normal ON-OFF method.

Table 2: Consumptions and Costs by Normal ON-OFF and Smart Methods

Objects	Methods		Savings	
	ON-OFF	PSO	kWh	%
Consumptions (kWh)	391.50	335.09	**56.40**	**14.41**
Costs (Rs)	742.76	599.28	**143.48**	**19.32**

The analysis of this case study provides a piece of information that energy consumption and cost of a house can be reduced by load shifting, peak clipping, and valley filling through scheduling of existing loads using the smart method under demand response. The energy cannot be supplied during curtailment in this case.

5.2. Case-II: Considering Loads and Energy Storage Systems with Curtailment

In this case, we have considered the loads as in Case-I as well as energy storage systems. The energy storage systems are plug-in hybrid electric vehicles and UPS systems. Thus, the total devices of a house are EWP, EWH, HVAC, PHEV, and UPS systems. These devices have to schedule for home energy management (with energy supply during curtailment). Here, price is the main parameter for the incorporation and scheduling of loads for the energy storage systems and utility power supply through normal ON-OFF and smart methods. The curtailment duration and slots are the same as in Case-I.

Fig. 6 shows the study results of this case in different situations. Where Fig. 6 (a) represents the scheduled load profiles when all devices of a house are considered. The interesting analysis is the curtailment and effect of ESSs. The electricity power is available during utility curtailment due to the energy storage system (UPS system). The UPS system can supply power to HVAC and/or EWP through the scheduling by normal ON-OFF and smart methods. Because the ratings of UPS system, HVAC, and EWP are 5, 3.5, and 1.5 kW, respectively, as given in Table 1. Hence, the peaks of the load profiles during curtailment are small in both methods, but after the curtailment, it goes to high consumption requirement for all devices of the house for the fulfillment of consumer comfort under set constraints. However, the peaks are less in the smart method compared to the normal ON-OFF method.

Table 3: Consumptions and Costs by Normal ON-OFF and Smart Methods

Objects	Methods		Savings	
	ON-OFF	PSO	kWh	%
Consumptions (kWh)	444.50	365.78	**78.72**	**17.71**
Costs (Rs)	843.083	630.74	**212.3461**	**25.19**

The incorporation effect of ESSs with the normal ON-OFF and smart method can be analyzed by given data in Table 3. The total energy consumption and cost by the normal ON-OFF method are 444.50 kWh and Rs. 843.043. Whereas, in the smart method, the total consumption and

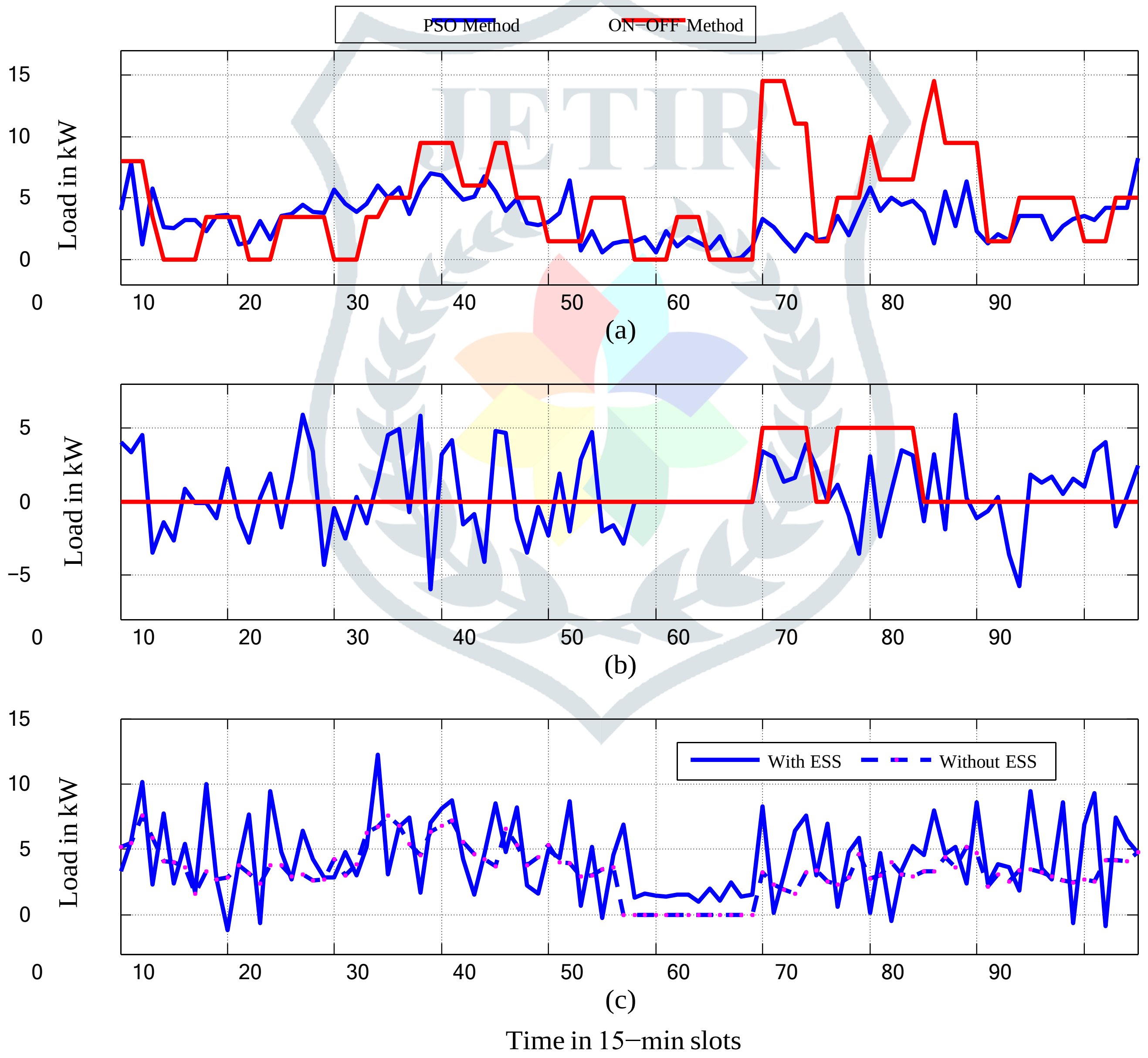


Fig. 6: (a) Load profiles of loads (EWP, EWH, and HVAC) by normal ON-OFF and smart methods, (b) Load profiles of PHEV and UPS system b

cost are 365.78 kWh and Rs. 630.74, which are 17.71 and 25.19 % less than the normal ON- OFF method. Moreover, the total consumption and cost of Case-II through the smart method are reduced by 3.3 and 5.87 %, respectively, compared to Case-I. This analysis shows the effective incorporation of ESSs with the smart particle swarm optimization method. However, the total consumption and cost in Case-II are slightly higher than in Case-I, because of additional ESSs charging loads.

Furthermore, the charging and discharging phenomenon of PHEV and UPS systems by both methods can be seen in Fig. 6 (b). The starting slot of incorporation and scheduling is set just after the curtailment so that more slots should be available. It is also taken care that both batteries do not process simultaneously so that higher peaks should not occur. The state of charge (SOC) levels of UPS system and PHEV are 25 and 50 kWh, respectively, as given in Table 1. Hence, the charging time of UPS system and EV is different from the normal ON-OFF method as shown, whereas the smart method has more positive and negative cycles for charging and discharging due to user comfort, load consumption, and cost constraints. The graphs also show the interruption periods between 48 to 60 slots, where the utility power is not supplied to the battery system.

Hence, the smart method is very useful for the incorporation of energy storage systems in the scheduling of house resources. This can also be analyzed from Fig. 6 (c). Where the two graphs are plotted with and without ESSs by the smart method. It is clear that the energy storage systems can supply power for interruptions through proper incorporation and scheduling. The graph without ESSs does not supply power during curtailment, while the graph with ESSs supplies power during the curtailment with frequent peaks and valleys due to the incorporation of the batteries (charging- discharging) for optimal adjustment and maintaining the required SOC levels for the set time of the slot.

In this case, the patterns of load profiles by the methods are similar to those in Case-I, because the considered loads and price are similar and the initial costs of the batteries are not considered due to consideration of the charging-discharging price. However, the load profiles obtained by the PSO method show more scheduling cycles due to the charging and discharging of the batteries. The peaks of consumption going to be higher than the previous Case-I due to the charging loads of the batteries. During the interruption of utility supply between slots 48 and 60, the scheduled oper- ations of the batteries are continued in discharging mode for the consumption of air-conditioning and electric water pump, and not in charging mode due to the unavailability of supply during the period.

5.3. *Case-III: Considering Loads and PV System with Curtailment*

In continuation of the case studies, in this case, we have analyzed the incorporation of dis- tributed generation with house loads (EWH, EWP, HVAC) for home energy management. Because DG has the potential to change the load profile characteristics of a system. Here, a rooftop solar photovoltaic system has been considered a DG. The PV system has been incorporated with utility for scheduling of the loads under demand response. Hence, the power supply for the considered loads is provided by the utility as well as the incorporated PV system. The curtailment duration and time slots are taken the same as in the previous cases. The PV incorporation with the utility for scheduling is quite significant as in the following results.

Load profiles of PV system incorporation and scheduling of the house loads by normal ON- OFF and smart methods are shown in Fig. 7. Where it is clearly shown in Fig. 7 (a) that the major contribution of the incorporated PV system is to supply power (HVAC and EWP) in the curtailment. The incorporated power by the normal ON-OFF and smart methods are shown in Fig. 7 (b) and Fig. 7 (c), respectively. The graph in the ON-OFF method is more discrete. This shows that the power generated by PV system is not better utilized. While, in the smart method, the graph is more stable. Hence, the incorporation of the power is better. This can be proved by the analysis of the data given in Table 4. The total energy consumption and cost evaluated by the ON-OFF method are 384.50 kWh and Rs.712.81, respectively. Whereas, these are 312.13 kWh and Rs. 540.71 in the smart method, which are 18.82 and 24.14 % less than the ON-OFF method. However, the energy price of PV system is more than the utility. Hence, the total cost of the incorporated PV power by the smart method is 1.05 % more than the study of Case-II.

5.4. Case-IV: Considering Loads, Energy Storage, and PV System with Curtailment

Case-IV is a comprehensive study of the incorporation and scheduling of the house resources. The energy storage and PV system are incorporated with utility in the scheduling of the house loads

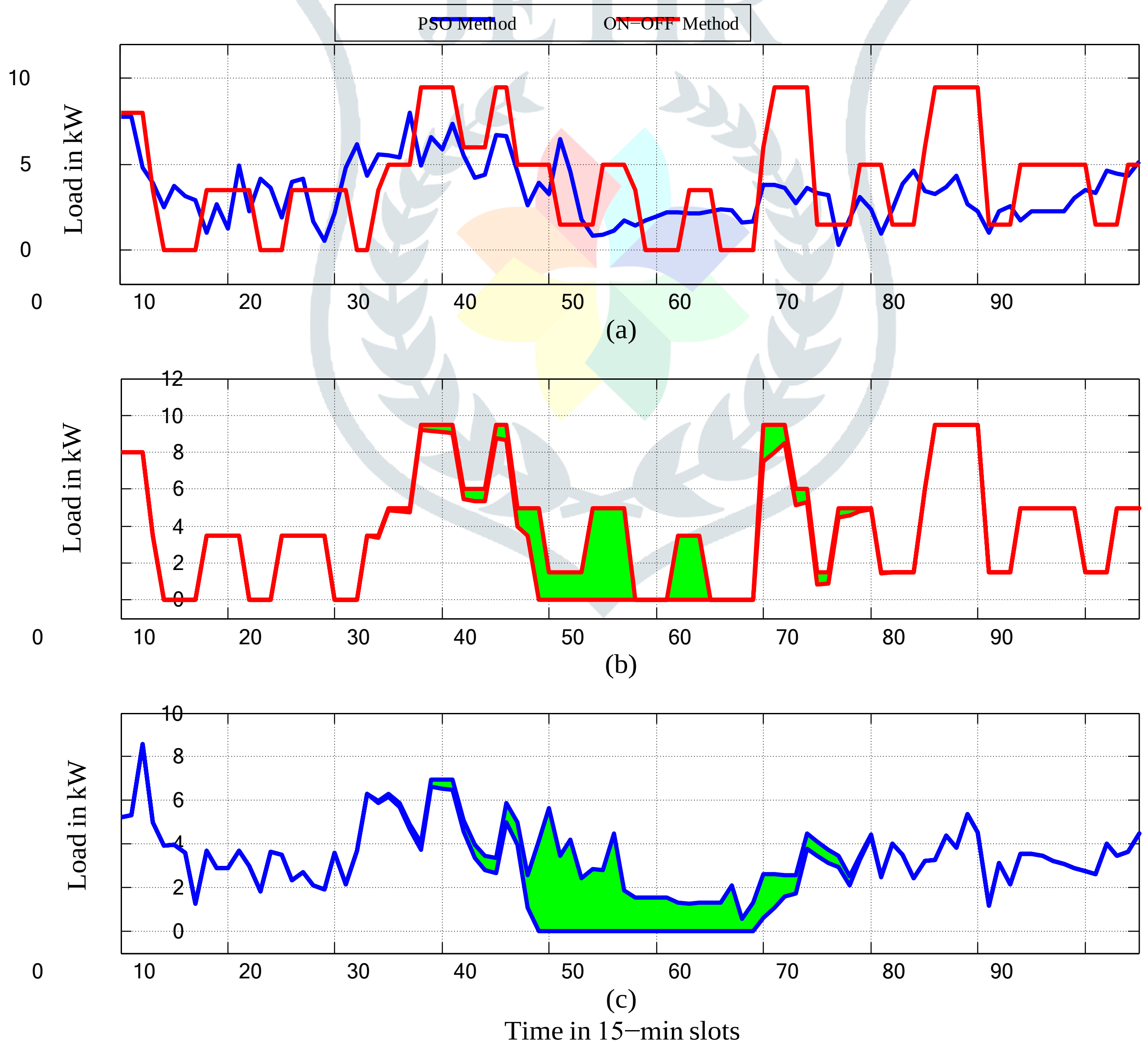


Fig. 7: (a) Load profiles by normal ON-OFF and smart methods, when photovoltaic system incorporated with utility power supply, (b) Incorporated power of PV generation by normal ON-OFF method, (c) Incorporated power of PV generation by smart method.

Table 4: Consumptions and Costs by Normal ON-OFF and Smart Methods

Objects	Methods		Savings	
	ON-OFF	PSO	kWh	%
Consumptions (kWh)	384.50	312.13	**72.37**	**18.82**
Costs (Rs)	712.81	540.71	**172.12**	**24.14**

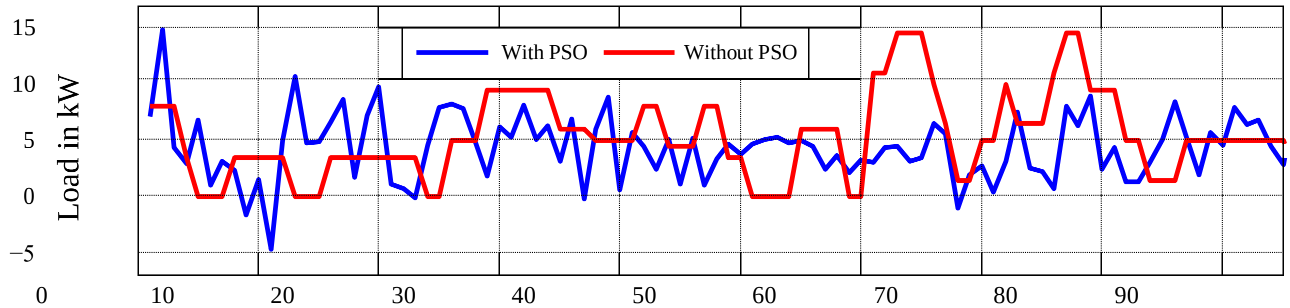
(EWP, EWH, and HVAC)) by the normal ON-OFF and smart methods considering curtailment. The house resources and curtailment parameters are taken the same as in the previous cases. The results and data of this case study are analyzed as follows.

Table 5: Consumptions and Costs by Normal ON-OFF and Smart Methods

Objects	Methods		Savings	
	ON-OFF	PSO	kWh	%
Consumptions (kWh)	470.50	320.91	**149.59**	**31.79**
Costs (Rs)	890.64	558.38	**332.25**	**37.30**

Fig. 8 shows three graphs of the results for different studies and views. Where Fig.8 (a) has two curves plotted by the normal ON-OFF and smart methods. The interesting analysis of the graph is for curtailment, peaks, and valleys. The peaks and valleys are clipped and filled more than in the previous cases by both methods. This can be proved by the given data of the results in Table 5. Where the consumption and cost evaluated by the normal ON-OFF method are 470.50 kWh and Rs. 890.64. Whereas these calculations by the smart method are 320.91 kWh and Rs. 558.38, which are 149.59 kWh and Rs. 332.25 less than the ON-OFF method. The reduction of the consumption and cost of the smart method to the normal ON-OFF method are 31.79 and 37.30 %. Hence, the smart method is more suitable for energy and cost saving. Because it provides more flexible adjustment of utility power as well as PV generation through the incorporation of energy storage under demand response. The energy storage has a characteristic of load as well as the

source at the time of charging and discharging, respectively. Therefore, this characteristic provides



(a)

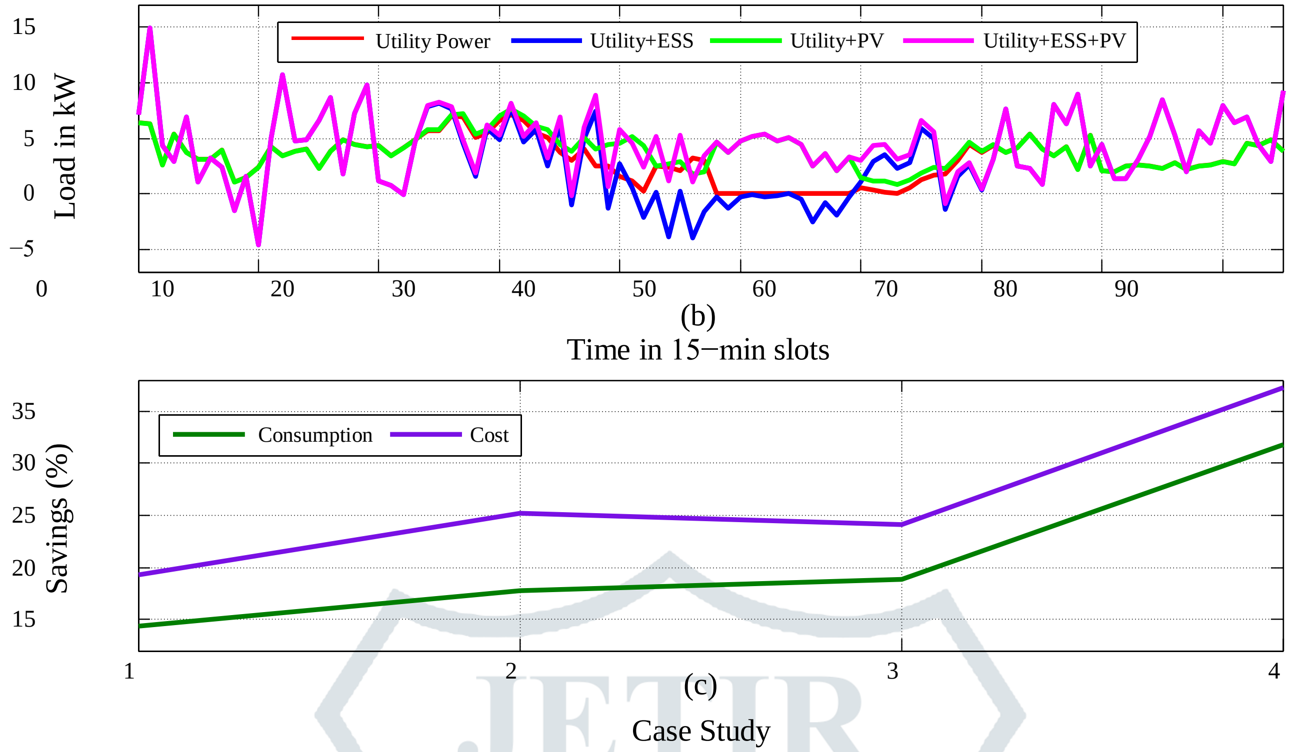


Fig. 8: (a) Load profiles by normal ON-OFF and smart methods, when energy storage and photovoltaic system incorporated with utility power supply, (b) Comparative load profiles by smart method, (c) Consumption and cost savings in different cases.

better flexibility for energy management and maintaining SOC level. This case supplies power to all loads of the house by the UPS system as well as the PV generation during the curtailment.

Moreover, these impacts of the incorporation (energy storage and PV system) can clearly be seen in Fig. 8 (b). The plots of this graph explain the comparative results obtained by the smart method for incorporation and scheduling. The comparative study of load profiles by smart method provides a comprehensive view to understand the home energy management with incorporation in the scheduling of different types of loads in the house.

First of all, we can analyze the individual impact of ESSs incorporation. A clear difference can be seen between the two plots of utility power and utility+ESSs with the curtailment. The plot of utility power has been taken from the scheduling of the loads supplied by utility power, where ESSs have not been considered. Whereas, in the plot of utility+ESSs, the incorporation of ESSs with the utility has been considered. It can be seen that the plot of scheduling with utility power is not of a dynamic nature. It has not any power supply during the curtailment. However, in the plot of ESSs, the incorporation of utility is more dynamic for flexible adjustment of utility energy under demand response. It has also an energy supply to the house load (air-conditioning) during curtailment through discharging of UPS batteries as shown. The incorporation of PV system with utility power is shown in the plot of utility+PV, where the major contribution of PV system is during utility interruption.

Thus, these load profiles show the individual interaction of energy storage and PV system with the utility using PSO method. These are different cases from each other for energy and cost savings. Because the energy storage systems have characteristics such as loads during charging as well as a source of energy supply during discharging. This characteristic of energy storage provides the flexible use of energy by charging-discharging. While the PV system has the char- acteristic of intermediate energy generation. However, the PV system reduces more energy con- sumption of the utility due to localized energy generation and provides reliable energy, when the utility system has a high energy price or is unable to energy supply. However, it is more costly than energy storage systems. This can be seen in Fig. 8 (c) and Case-III.

Furthermore, the plot of utility+ESSs+PV shows the effect on load profiles when energy storage and PV system incorporate together with the utility through scheduling by PSO method.

This plot clearly indicates the significance of each case compared to others. In this graph, the study of interruption duration is more interesting. Because the incorporation of energy storage and PV system plays an important role in the fulfillment of consumer satisfaction without utility supply inthis period.

Fig. 8 (c) shows the comparative importance of each case study in terms of cost and con- sumption savings using PSO. Because it is plotted with savings of energy consumption and cost versus different case studies with PSO method. As shown, the savings are minimum in Case-I. But, it is increased in Case-II due to the incorporation of energy storage systems. While the in- corporation of PV system is less effective for consumption and cost saving due to its intermediate power generation characteristics and higher price of energy as in Case-III. However, it is more effective with the incorporation of energy storage systems for savings as in Case-IV.

6. Conclusion

This research article provides an important algorithm for home energy management (HEM). The algorithm incorporates energy storage systems (ESSs) and distributed generation (DG) with utility supply under the real-time price. The incorporation and scheduling have been carried out by normal ON-OFF and smart particle swarm optimization (PSO) methods considering a curtailment duration and end-user comfort. It is proved in different case studies of this article that the algorithm designed with PSO method is the best for home energy management and cost reduction. It is also seen that the plug-in electric vehicle (PHEV), uninterrupted power supply (UPS), and PV system are the best suitable devices for incorporation and scheduling of house loads for bill reduction as well as power supply during curtailment. Furthermore, demand response (DR) is the best tool for the incorporation and scheduling of house devices. Hence, it is a simple and realistic scheduling algorithm in MATLAB environment which may have a scope of implementation in a large numberof houses.

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