Electricity Scheduling for Residential Prosumers with Demand Response

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***Abstract*—The advent of smart grid provided ample opportunities for consumers to adopt small-scale renewable energy generation and become prosumers. In addition to this, advancement in information, communication and control technologies has equipped prosumers with smart home appliances. To extract energy saving and lesser cost of electricity, residential prosumers perform energy management in accordance with renewable energy generation, energy storage, responsive appliances, and electricity price. This requires optimal scheduling of prosumer demand with their operational preferences of appliances in order to perform energy saving. In this regard, this paper proposes a novel optimization based control of different (characteristics) appliances to schedule electricity for residential prosumers. Prosumer demand preferences for appliances are considered with operational constraints of appliances. Time-of-use tariff and day-ahead real time pricing is used for electricity scheduling and its impact is assessed. To increase the energy efficiency and the accuracy of the required results, scheduling time horizon of 24 h is divided into 144 small time slots, each of 10 min duration. The simulation results show the reduction in the cost of electricity and attainment of the highest possible satisfaction level of prosumers.**

***Index Terms*—Demand Response; Prosumer Scheduling.**

I. Introduction

Adoption of power generation from renewable energy sources, such as wind and solar power, play a critical role in transition towards a low-carbon power system. Moreover, the penetration of small-scale distributed renewable generation (RG), energy storage system, and electric vehicles is increasing and traditional power consumers are becoming prosumers (producer as well as consumer of electricity) [1]. It has been estimated that RE penetration from prosumers on distribution network in 2050 would reach approximately 80 GW, which represents 30-50% of total demand in Australia [2]. In order to achieve potential benefits from adoption of RG by consumers, a residential automation of appliances is required to benefit both prosumers and grid. Prosumer perform scheduling of its load (appliances) and storage as per the RG to minimize electricity cost. Prosumers have various appliances each having its own energy consumption and operation characteristics. As per elasticity of energy consumption pattern, prosumer residential appliances are categorized into three categories, namely, deferrable appliances, thermal appliances and critical appliances [3-6]. Deferrable appliances can be further classified into non-flexible and flexible deferrable appliances. It is important to have the appropriate energy consumption and operation model for each appliance while scheduling to minimize electricity cost. Due to intermittency in power output from RG, prosumer face energy mismatch (excess/deficit) during whole day depending upon RE type and would rely on grid to fulfil energy requirement. From grid perspective, prosumers play an important role in operation of the grid by minimizing/transferring their electricity consumption from peak hours to off-peak hours in response to fluctuating electricity prices (demand response (DR)). Retailer from gird offer price-based DR programs to motivate prosumers financially to manage their residential appliances in efficient way for minimizing electricity cost and peak to average ratio. Prosumer interaction with electricity grid through communication network, utilizing two-way communication between grid and prosumers, to provide demand response (DR) [7-8]. With DR and RG, prosumers schedule their energy consumption and operation of their appliances with RG to minimize electric bill based on offered grid electricity prices and appliance preferences. With an optimal schedule of residential appliances and storage units, prosumer determine the amount of surplus RG to sell to the grid (or retailer). According to [7-10], different dynamic pricing schemes such as Time-of-Use (TOU), Real Time Pricing (RTP) are proposed to provide motivation to consumers to reduce load in peak hours. DR problems in the smart grid have been actively studied in literature with respect to active consumers. However, the optimal appliance scheduling for prosumers having RG and detailed characteristics of various appliances together with different price-based DR program has not been well investigated yet.

In this paper, a novel optimization based scheduling of different appliances and RG is proposed in accordance with offered price-based DR by grid (retailer). The scheduling framework consider three different characteristics of appliances mostly found in residential model with TOU and real-time day-ahead electricity price. The proposed scheduling framework aims to reduce the prosumers' electricity cost, whilst maintaining their comfort.

The rest of this paper is organized as follows. Section II provides details of prosumer appliances description and their mathematical modelling. Numerical results and conclusion are provided in section III and IV respectively.

II. Prosumer System Description and Energy Scheduling

Distribution network prosumers having renewable generation, battery energy storage and load is considered. Prosumers, when their energy consumption is greater than generation, buy deficit energy from a grid/retailer through TOU and RTP. Alternatively, when energy consumption of prosumer is less than the generation, surplus energy is sold to the retailer at the export price specified under Feed-in Tariff (FIT) scheme. Prosumers schedule their battery usage and demand to trade with retailers, based on their generation profile and offered TOU/RTP and FIT, to minimize its overall cost of electricity. The consumption schedule of flexible deferrable appliances, curtailable appliances and thermal appliances and decisions for selling/buying surplus/deficit energy to/from grid are the main outputs of minimized cost optimization. Prosumer get benefit from selling electricity to the grid. The cost minimization optimization model decides in which time frame prosumer sell the RG to the grid or when prosumer consume electricity as per DR program. In addition to this, decisions for charging and discharging are made for the battery energy storage. This section provides mathematical modelling of prosumer's RG, appliances, battery energy storage and cost function

A. Renewable Generation

There are various types of Renewable Energy (RE) technologies that prosumer may own, such as wind, photovoltaic (PV) and biomass. RG from PV is considered in this paper. Based on historical solar irradiation data, day-ahead solar irradiation is forecasted. In this work, neural network toolbox (nntool) of MATLAB R2014a is used to forecast day-ahead solar irradiation with Levenberg-Marquardt Feed forward Back Propagation Algorithm. With forecasted data, equivalent PV output (power generation) is calculated. The main component in PVs plant is PVs cells which convert the solar irradiance and temperature into direct current. With the use of power converter, the output direct current is converted to alternating current and power output is calculated as [11]-

$$PV_t = PV_{max} I_t F \tag{1}$$

PV_t denotes the maximum available renewable power of in time slot t. The entire time interval T(24 hour) is divided into t sub-intervals (144 sub-intervals, 10 minute duration each). It is assumed that prosumer has installed RE plant for its own use only. Energy excess is shared with grid to get economic benefit. Therefore, zero marginal generation cost is assumed.

B. Residential Appliance Modelling

Prosumers' residential appliances have different levels of operating flexibility. The primary focus for prosumer scheduling is on flexible deferrable appliances, curtailable appliances and thermal appliances. Controlling these time-shiftable appliances would increase prosumers demand elasticity. Energy consumption by appliances at period t consists of energy consumption from deferrable appliances DA_t, thermal appliances TA_t and critical appliances CA_t. Total load (energy consumption l_t) from all appliances A at time t is given as-

$$l_t = DA_t + TA_t + CA_t \tag{2}$$

1) Deferrable appliances: It involves appliances whose starting time can be change throughout the day in response. These appliances can further be classified as non-flexible deferrable appliances and flexible deferrable appliances. Therefore, energy consumption from deferrable appliances DA_t at time t is given as

$$DA_t = DA_t^{FD} + DA_t^{NFD} \tag{3}$$

- Flexible deferrable appliances: It includes all interruptible appliances whose operation can be managed such refrigerator and oven. Eq. (4) illustrates energy consumption of flexible deferrable appliances [7-8]. $\phi_{FD,t}$ is the binary indicator (1 means ON and 0 means OFF) for the appliance status at time t. The operational time of appliance should be throughout its allowable operational interval (begin b_{FD} and end e_{FD}) which is restricted by (5), where U_{FD} is number of required operational period of appliance.

$$l_{FD,t} = \sum_{A \in FD} \phi_{FD,t} \cdot l_{FD} \tag{4}$$

$$\sum_{t \in [b_{FD}, e_{FD}]} \phi_{FD,t} = U_{FD} \quad \forall FD \tag{5}$$

- Non-flexible deferrable appliances: It includes all non-interruptible appliances whose operation follow a pre-defined power profile such as washing machine. Eq. (6) and Eq. (7) illustrates energy consumption of non-flexible deferrable appliances [7-8]. The non-interruptible operation is modelled using (8). The relation between start-up $y_{NFD,t}$ / shut-down $z_{NFD,t}$ indicators and status of appliance $\phi_{NFD,t}$ is presented in (9-10).

$$l_{NFD,t} = \sum_{A \in NFD} \phi_{NFD,t} \cdot l_{NFD} \tag{6}$$

$$\sum_{t \in [b_{NFD}, e_{NFD}]} \phi_{NFD,t} = U_{NFD} \quad \forall NFD \tag{7}$$

$$\sum_{h=t}^{t+U_{NFD}-1} \phi_{NFD,h} \geq U_{NFD} \cdot y_{NFD,t} \quad \forall t \leq NP - U_{NFD} + 1 \tag{8}$$

$$z_{NFD,t} + y_{NFD,t} \leq 1 \quad \forall NFD \tag{9}$$

$$y_{NFD,t} - z_{NFD,t} = \phi_{NFD,t} - \phi_{NFD,t-1} \quad \forall NFD \tag{10}$$

2) Thermal appliances: It includes appliances whose power consumption can be controlled to maintain the temperature within thermal comfort of prosumer such as HVAC (heating, ventilation, and air conditioning) [3,9]. Thermal loads TA_t encompass devices like air conditioners, that aim at keeping a system's (e.g., a room) temperature $\theta_{TA,t}$ within a certain range i.e. between $\Theta_{TA,i}^{\min}$ and $\Theta_{TA,i}^{\max}$. Their operation is modelled as-

$$\Theta_{TA,i}^{\min} \leq \theta_{TA,t} \leq \Theta_{TA,i}^{\max} \tag{11}$$

$$\frac{\mu_{TA,t}}{C_{TA,t}}(\Theta_{TA,t}^{ext} - \theta_{TA,t}) + \frac{\eta_{TA,t}}{C_{TA,t}} l_{TA,t} = \frac{\theta_{TA,t+1} - \theta_{TA,t}}{\Delta\tau} \tag{12}$$

$$\phi_{TA,t} l_{TA}^{\min} \leq l_{TA,t} \leq \phi_{TA,t} l_{TA}^{\max} \tag{13}$$

The on-off constraints of thermal appliances are modelled in (12-13), where $\mu_{TA,t}$ is thermal conductivity, $C_{TA,t}$ is thermal capacity and $\eta_{TA,t}$ is thermal efficiency of thermal load. $\Theta_{TA,t}^{ext}$ is day-ahead ambient temperature which forecasted based on historical 10 minutes ambient temperature data, similar to solar irradiation. $l_{TA,t}$ is algebric power consumption of thermal appliances during time t and $\Delta\tau$ is duration of time period.

3) Critical appliances: This sort of appliance activities is uncontrolled and must be maintained without interference [5,8]. Energy consumption of critical appliances CA_t is formulated as

$$l_{CA,t} = \sum_{A \in CA} \phi_{CA,t} \cdot l_{CA} \tag{14}$$

$\phi_{CA,t}$ is one of the decision binary variables of prosumer load control whereby the preferred operation periods of critical appliances are reported. Each nonresponsive appliance has a definite operation time i.e. operation interval (b_{CA}, e_{CA}). Since there can be several ON-OFF intervals for one appliance, determined operation time is exposed by factor f in the formulation. So

$$\sum_{t \in [b_{CA}, e_{CA}]} \phi_{CA,t} = f \cdot U_{CA} \tag{15}$$

It is assumed that the operation periods of critical appliances should be consecutive which is restricted by (16).

$$\sum_{h=t}^{t+U_{CA}-1} \phi_{CA,h} \geq U_{CA} \cdot y_{CA,t} \qquad \forall t \leq NP - U_{CA} + 1 \tag{16}$$

The relations between $y_{CA,t}$ and $z_{CA,t}$, which are the start-up and shut-down indicators, and $\phi_{CA,t}$ are according to

$$z_{CA,t} + y_{CA,t} \leq 1 \tag{17}$$

$$y_{CA,t} - z_{CA,t} = \phi_{CA,t} - \phi_{CA,t-1} \tag{18}$$

C. Energy Storage (ES)

Prosumer uses ES such as battery to handle renewable intermittency and reduce dependency on retailer by charging and discharging according to retailer price, generation and load condition throughout the day. The battery dynamics with total battery capacity $\bar{S}$ is defined as

$$s_t = s_{t-1} + (\eta^c r_t^c - \frac{r_t^d}{\eta^d})\Delta t \quad \forall t \in T \tag{19}$$

where η^c and η^d are charging and discharging efficiency of battery. The charging r_t^c and discharging r_t^d power of battery should satisfy the following constraints:

$$0 \leq r_t^c \leq \bar{r}_t^c n_t \quad \forall t \in T \tag{20}$$

$$0 \leq r_t^d \leq \bar{r}_t^d m_t \quad \forall t \in T \tag{21}$$

$$\begin{cases} n_{i,t} & \in & \{0,1\} \\ m_{i,t} & \in & \{0,1\} \\ n_{i,t} & + & m_{i,t} \leq 1 \end{cases} \tag{22}$$

Cost of battery is considered as battery degradation caused by repetitively charging and discharging by limiting daily cycles.

D. Prosumer Cost Function

The objective of prosumer is to minimize its total electricity cost considering the preferences and the priorities of the prosumers over appliances. As per price-based DR program by grid/retailer, the prosumers energy cost under TOU/RTP (λ_t^b) and FIT scheme (λ_t^s) is calculated as follows-

$$\text{Min} \quad Cost = \sum_{t \in T} \lambda_t^b Q_t^b - \lambda_t^s Q_t^s \tag{23}$$

where Q_t^b and Q_t^s is amount of energy purchased and sold to the grid. The power balance equation for prosumer to satisfy its demand is

$$PV_t + Q_t^b + r_t^d = Q_t^s + r_t^c + l_t \tag{24}$$

III. Numerical Study

A prosumer with rating of 2KW PV panel is considered and with forecasted solar irradiance the PV output is calculated using (1) as shown in Fig.1. Table I provides operational details of flexible deferrable, non-flexible deferrable and criticalappliances. The data for thermal load and 2 KW ES is shown in Table II. The TOU and RTP profile is shown in Fig.1 and FIT is assumed to be fixed as 1 cent/KW. This section analyzes the proposed prosumer scheduling (23) as mixed-integer programming solved using GAMS software. Two case study is considered based on pricing scheme offered by retailer as 1) Case 1: With RTP 2) Case 2: With TOU

TABLE I: Thermal appliance and ES data

$\mu_{TA,t}$	$C_{TA,t}$	$\eta_{TA,t}$	$\Theta_{TA,i}^{\min}$	$\Theta_{TA,i}^{\max}$
4	0.4	3.5	19	25
SOC_{min}	SOC_{max}	$SOC_{initial}$	η^c	η^d
0.4	1.5	0.5	0.97	0.95

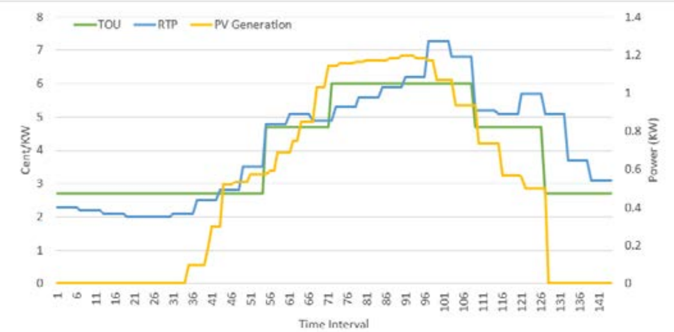
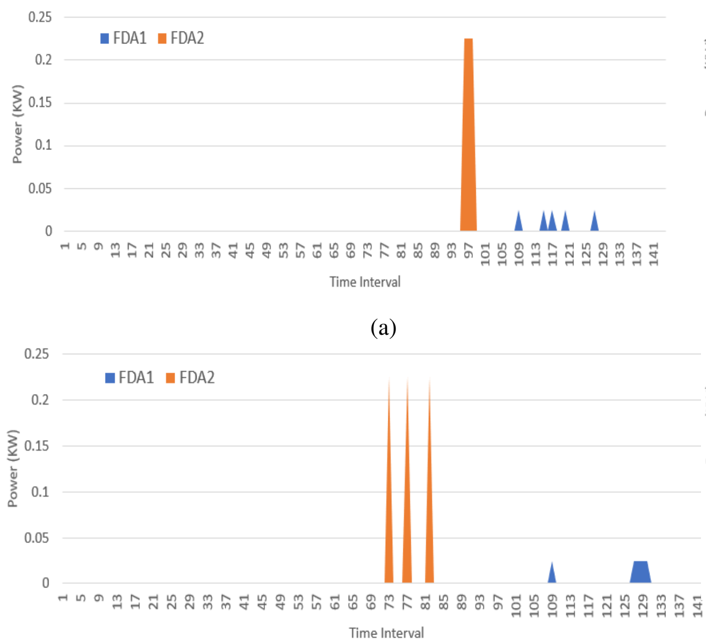


Fig. 1: PV generation, TOU and RTP.



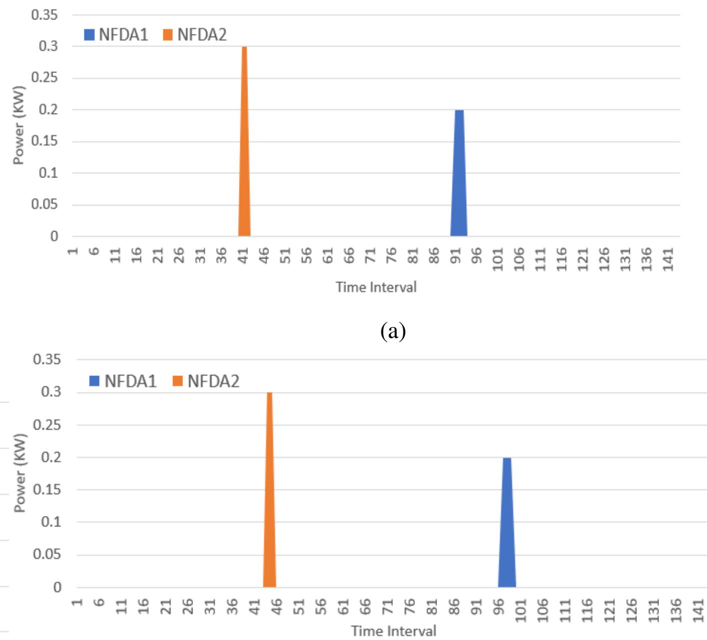
(a)

(b)

Fig. 2: Flexible deferrable appliances scheduling under (a) RTP and (b) TOU.

A. Case 1: With RTP

Prosumers schedule their ES and appliances to trade with retailers, based on their generation profile and offered RTP and FIT, to minimize its overall cost of electricity. The ON/OFF period of flexible deferrable appliances is shown in Fig.2 (a). It can be seen that the operation of such appliances can be interruptible and it can be seen based on RTP first flexible deferrable appliance need to operate for 5 time intervals between the time interval of 109-132 as illustrated in Table I. It can be seen from Fig.1. that it is ON during t109, t115, t117, t120 and t127. Similarly operation of second flexible deferrable applainace is shown in Fig.2 (a). The non-flexible deferrable appliance should operate non-intrruptiblaly but their operation can be shifted. For e.g. the first NFD appliance need to operate for 2 continuous time interval but can be online in between 91-114 or 1-40 as shown in Table I and their operation schedule is shown in Fig. 3 (a). The schedule of critical appliances is uncontrolled and maintained without interference as shown in Fig. 4 (a). The forecasted ambient temperature is shown in Fig. 5. To power required by HVAC to maintain the indoor temperature in pre-defined range is shown is Fig. 5. The battery dynamics for different time intervals can be seen in Fig. 6. The detailed scheduling framework is illustrated in Fig. 7 (a) for RTP providing time interval where prosumer purchase/sell electricity from/to retailer. The cost occured to prosumer under RTP scheme is 70.43 Cents for the whole day.



(a)

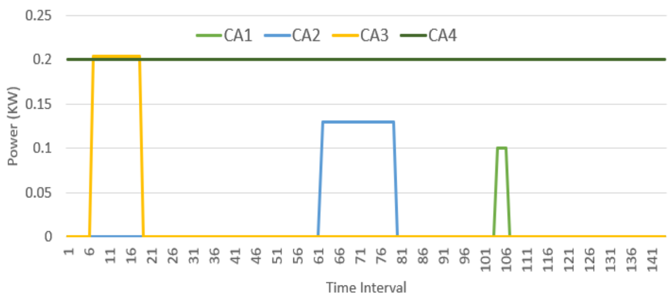
(b)

Fig. 3: Non-flexible deferrable appliances scheduling under (a) RTP and (b) TOU.

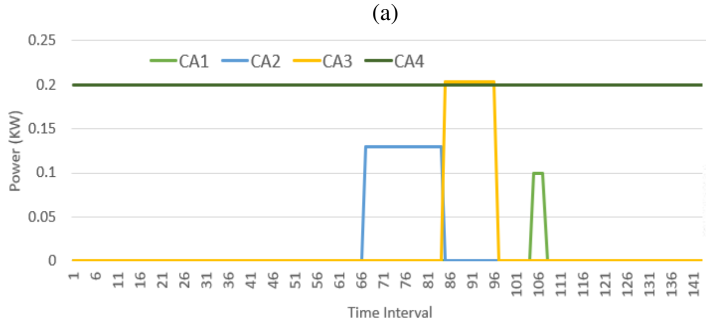
B. Case 2: With TOU

Prosumers schedule their ES and appliances to trade with retailers, based on their generation profile and offered TOU and FIT, to minimize its overall cost of electricity. The ON/OFF period of flexible deferrable appliances is shown in Fig.2 (a). It can be seen from that first appliance is ON during t109, t127-t130. Similarly operation of second flexible deferrable applainace is shown in Fig.2 (b). The non-flexible deferrable appliance should operate non-intrruptiblaly but their operation can be shifted as shown in Fig. 3 (b). The schedule of critical appliances is shown in Fig. 4 (b). The battery dynamics for different time intervals can be seen in Fig. 6. The detailed scheduling framework is illustrated in Fig. 7 (b) for TOU providing time interval where prosumer purchase/sell electricity from/to retailer. The cost occured to prosumer under RTP scheme is 58.94 Cents for the whole day.

As compared to RTP, the prosumer is benefitted more under the TOU scheme. RTP are more dynamic and changes in every



(a)



(b)

Fig. 4: Critical appliances scheduling under (a) RTP and (b) TOU.

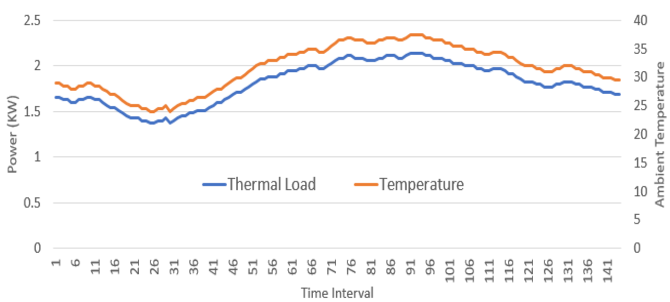


Fig. 5: Thermal appliance power with ambient temperature.

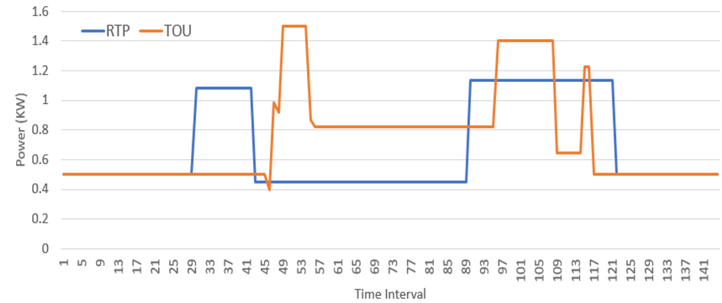
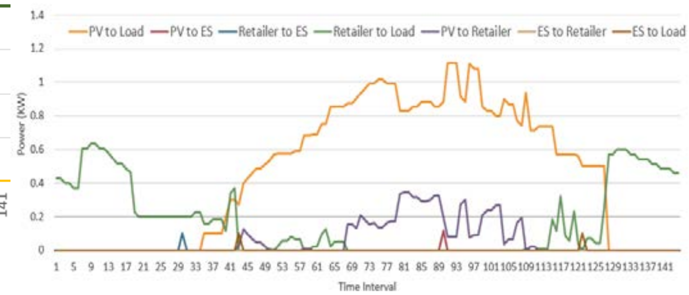
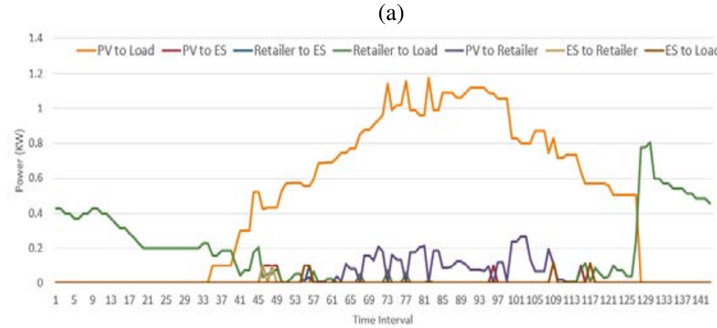


Fig. 6: SOC of ES under RTP and TOU



(a)



(b)

Fig. 7: Prosumer detailed scheduling output under (a) RTP and (b) TOU.

time interval, thus, the contineous operation of non-flexible deferrable, thermal and critical appliances increases the cost for prosumers. Whereas, in TOU, due to block pricing, the contineous soperation of these appliances shifted to non-peak peak period or period where PV generation is available. This reduces the overall cost for prosumers. For flexible deferrable appliances, the RTP is more suitable as their operation can be intrrupt as per price. These appliances mainly operate continuous under TOU as analyzed from Fig. 2 (b).

IV. Conclusion

This paper presents the optimal consumption of prosumers while implementing DR programs by retailer. The prousumer scheduling framework is modelled using different characteristics of appliances that are mostly found in resident. The scheduling framework aims to reduce the prosumers' electricity cost, whilst maintaining their comfort. Prosumer's cost function is caluculated under TOU and RTP schemes and comparison is performed. As per the output of RE generation, the energy consumption of different type of appliances and their preferred operational time for minimizes cost is the output of scheduling problem. From result comparison, it can be seen that TOU provides more benefits to prosumers as compared to RTP scheme. Uncertainity of PV and load can be considered as a future scope of proposed framework.

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