Dynamic Programming Based Home Energy Management Unit Incorporating PVs and Batteries

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***Abstract*—Decreasing cost of solar PV systems have resulted in a rapid uptake of residential rooftop Photovoltaic (PV) systems across the globe. However, recent policy changes in Australia is incentivizing residential customers to install battery energy storage systems (BESSs) for effective utilization of their solar sources. This paper proposes an improved dynamic programming (DP) based home energy management (HEM) unit for grid connected residential PV systems equipped with BESSs. The proposed HEM scheme aims to minimize daily cost of electricity for residential customers by efficiently scheduling and managing PV-BESS systems. The impact of BESS degradation also included in the energy management model. Furthermore, flexible and constrained operation strategies of BESSs are proposed and the scheduling of PV-BESS systems is investigated for three different electricity price mechanisms such as constant, time of use (TOU) and dynamic tariffs in view of FIT rates available for new and old solar customers. The proposed HEM scheme will help residential customers compare the profitability of their installed PV-BESS systems under different price structures. Hourly simulations using PV generation and different load data are used to verify the effectiveness of the proposed HEM unit.**

***Index Terms*— Battery energy storage system (BESS), battery degradation, dynamic programming (DP), electricity tariffs, home energy management (HEM), photovoltaic (PV).**

I. Introduction

In recent years, installation of rooftop solar panels for residential or commercial power supply in Queensland State of Australia has increased dramatically due to some favourable environmental and economical reasons. Currently about 30% of homes in the state have installed solar systems with capacity of under 10 kW which equals to around 1468 MW [1]. Large amount of sunshine, decreasing installation cost of solar Photovoltaic (PV) and rising electricity price (EP) all together have motivated households and businesses to install PVs as an option to decrease power purchase from electricity utilities.

Until a couple of years ago, feed-in tariff (FIT) incentives were also another and possibly the main motive for PVs installation in Australia, when FIT rate were higher than the cost of grid electricity and solar panels were considered as a good investment. Nowadays, FIT rate has been reduced to about 1/4 the EP drawn from the grid and are state-mandated, so new customers of PVs cannot be benefited from generous FIT incentives [2]. However, PV systems are still

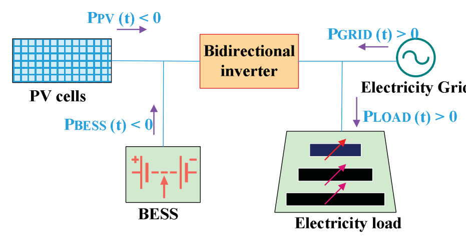

Fig. 1. Schematic of residential rooftop PV-BESS system

worthwhile investment thanks to the considerable decrease in solar panels prices, but how to best use a system has changed. One advisable solution for PV investors is offered by battery energy storage systems (BESSs) which enable them to save money by storing energy produced by PV in the daytime for their own consumption during night hours, instead of wasting it into the grid at a small rate. Moreover, BESSs can be exploited to alleviate the uncertainty and intermittency related to the power production of PVs.

There is also another important consideration when it comes to installation of BESSs; switching power tariffs from a flat rate to a time variable rate such as time-of-use (TOU) and dynamic tariffs. Under hourly tariffs, solar system owner can make good use of ‘energy time-shift’ concept which originates from price differential between on- and off-peak periods by charging batteries from solar energy on off-peak time for later use on on-peak time [3] . Additionally, a storage system can unlock the possibility of ‘tariff arbitrage’. Tariff arbitrage is the practice of purchasing electricity from the electricity grid when it is cheap, and storing it for later use when grid electricity is expensive. It is the same basic concept as storing solar energy for later use, but charging with energy from grid rather than from solar panels [4] However, at the moment integrated BESSs and PV systems are not allowed to draw energy from the distribution grid [5].

Home energy management (HEM) involves optimally scheduling the power flows among each component so that the total operating cost can be minimized within a given period of time [6, 7]. Some works have addressed this problem and several techniques such as logic-based geometrical method [8], particle swarm optimization [9], and linear optimization method [10] have been presented. With integration of BESSs to grid-connected residential or commercial PVs, as shown in

Fig. 1, HEM is gaining more importance. This paper deals with optimal energy management for a grid connected residential PV generator with BESS for minimizing daily cost of electricity consumption from the grid. The primary aim of this study is to reduce daily electricity bill of the owner by efficiently scheduling and managing the use of the storage element. Also, operational effects on BESS degradation are taken into consideration by adding a degradation cost to have a better evaluation for the profitability of the HEM system. A forward dynamic programming (DP) is utilized as the power management optimization tool to optimally dispatch hourly power flow among individual components within a daily scheduling horizon. The scheduling of PV-BESS systems is highly related to EP structure, therefore this study takes into account three different price schemes, namely constant, TOU, and dynamic tariffs. Additionally, two charging/discharging strategies for BESSs, namely constrained and flexible operation, are developed. Energy scheduling is investigated for each operation strategy under different tariff models. Also, impact of recent FIT rate change on the cost-effectiveness of PV-BESS systems is analyzed. This study is helpful, from the perspective of residential customers, in evaluating economical advantageous of PV-BESS systems under different EP mechanisms. This research is organized as follows. The mathematical modeling of system and HEM technique is presented in Section II. Validation of the effectiveness of the developed model is illustrated in Section III. Finally, Section IV gives the conclusions.

II. Problem Description

A. System Modelling

The main components of the hybrid system include the customer load, the PV panels, the BEES, the converters, and the distribution grid, as shown in Fig. 1.. The focus of this work is to find the optimal energy flow scheduling so that the energy bill of the system owner is minimized over the day. Thus, the objective function of the optimization problem is to minimize total cost of electricity consumption (CoEC) as follows:

$$\begin{aligned} CoEC &= \sum_{t=1}^{T}\left[CP(t)+CR(t)+C_{BD}(P_{BESS}(t))\right] \\ &= \sum_{t=1}^{T}[(\underset{P_{Grid}(t)>0}{P_{Grid}(t)c(t)})+(\underset{P_{Grid}(t)<0}{P_{Grid}(t)FIT(t)})+C_{BD}(P_{BESS}(t))] \end{aligned} \tag{1}$$

where P_{Grid} is the exchanged power with the grid, P_{BESS} is the power of BESS, and *c(t)* is the grid EP at time '*t*'. The first part of the objective function is the cash paid (*CP*) by the owner for electricity imported form the utility. The second part relates to the cash received (*CR*) from exporting power into the grid. According to the power sign convention in Fig. 1, the cash paid by the system owner is positive and the cash received is negative. The third part of the CoEC corresponds to the cost of BESS degradation (C_{BD}). Two most determinant factors on BESS lifetime are the number of charge/discharge cycles and the maximum depth of discharge (DOD). Degradation cost is determined as follows [11]:

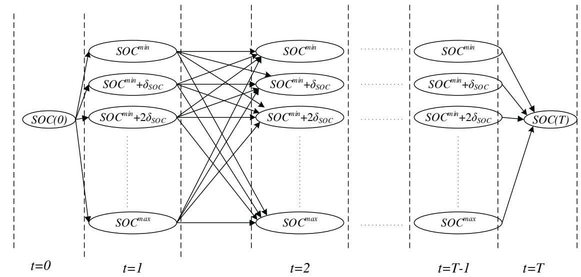

Fig. 2. Graph representation of SOC space and management process

$$C_{BD}(P_{BESS}(t)) = \frac{C_{BESS}\times\left|P_{BESS}(t)\right|}{2N(t)DOD(t)E_{BESS}(t)\eta_{BESS}^{ch/dis2}} \tag{2}$$

where C_{BESS} is the BESS initial value (\$/kWh), N is the number of life cycles, E_{BESS} is the capacity, and $\eta_{BESS}^{ch/dis}$ is the charge/discharge efficiency of BESS. The number of life cycles, DOD and capacity at time t are calculated by:

$$DOD(t) = 1 - SOC(t) \quad \forall t \in T \tag{3}$$

$$N(t) = \alpha DOD(t)^{-\beta} e^{-\chi DOD(t)} \quad \forall t \in T \tag{4}$$

$$E_{BESS}(t) = E_{BESS}(t\text{-}1) - \frac{E_{BESS,rated}}{N(t)} \quad \forall t \in T \tag{5}$$

where SOC is the state of charge of BESS and α,β and χ are curve fitting parameters. It is worth mentioning that this study assumes that BESS is maintained at its nominal operating temperature, thus temperature impact on lifetime is ignored.

The constraints of the HEM unit are as follow:

$$P_{Grid}(t) = P_{PV}(t) + P_{BESS}(t) + P_{Load}(t) \quad \forall t \in T \tag{6}$$

$$SOC^{\min} \le SOC(t) \le SOC^{\max} \quad \forall t \in T \tag{7}$$

$$P_{BESS}^{\min} \le P_{BESS}(t) \le P_{BESS}^{\max} \quad \forall t \in T \tag{8}$$

$$SOC(T) = SOC(0) \tag{9}$$

$$P_{Grid}(t) \le P_{Grid}^{\max} \quad \forall t \in T \tag{10}$$

Constraints (6) is the power balance constraint of the system, constraints (7)-(9) are related to the BESS [12]. Constraint (9) guarantees that the final energy level in the storage device at the end of the day should be equal to the initial energy stored for the next day scheduling. The charging/discharging power of BESS is calculated by [12]:

$$SOC(t) = SOC(t-1)(1-\eta_{BESS}^{decay}) - \frac{P_{BESS}(t)}{E_{BESS}(t)} \quad \forall t \in T \tag{11}$$

where η_{BESS}^{decay} is the electricity loss ratio. Constraint (10) is to prevent any voltage limits violation resulted from high power injection to the distribution grid [6].

HEM relies on employing robust forecasting techniques. It is assumed that hourly predictions of acceptable accuracy for energy consumption and PV output power are available for the next scheduling period.

B. Dynamic Programming

DP is an optimization technique for systems of dynamic nature that simplifies an intricate and large problem by

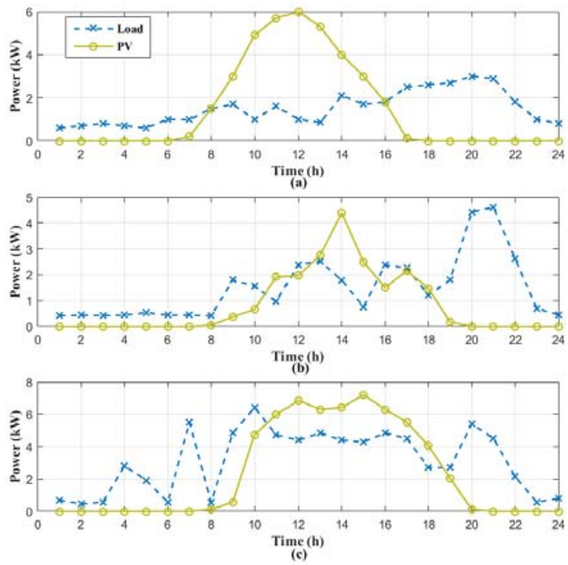

Fig. 3. PV generation and load profile for (a) H1, (b) H2, and (c) H3

breaking it down into several simpler sub-problems in a recursive manner so that optimal solutions for sub-problems in each given step can be calculated [6]. The advantage of DP to other optimization methods is that it is applicable for problems with the objective function and constraints of any nature, i.e. linear or not, convex or nonconvex, etc.

First step to employ DP is to specify state of the system at any time "*t*" by a set of quantity called state variables. In the proposed HEM model, the state of system is represented by the SOC of the BESS which discretized with a step size of δ_{SOC}. At any time '*t*', the batteries can take any of the discretized values of δ_{SOC} in the range of constraint (7). Any transition between two states corresponds to a specific value of battery power, so P_{Grid} is calculated according to (6) considering P_{BESS} and forecasted values of P_{Load} and P_{PV} for that '*t*'. In other words, the transition from a certain SOC at time '*t*' to another SOC at '*t*+1' is done by energy supply to or from the BESS, then the amount of energy to draw from or feed into the grid can be determined. In evaluating the transition from one state at '*t*' to another state at '*t*+1' all SOCs that satisfy (7) should be taken into account. Fig. 2 depicts graph of SOC space for the proposed HEM model. In brief, the problem is to discover the series of SOC transition from the initial time point to the final time point such that the total cost over the entire period is minimized.

Starting from *t*=1, all connections between the initial state and every state at *t*=1 are evaluated to check the possibility of the transition. A transition is not possible if it does not satisfy constraint (10). Also, due to the current regulations grid connected BESSs are not allowed to be charged from the distribution grid. Therefore, under constrained operation of BESS and when no solar power is available (*i.e.* when P_{PV}=0) any transition with ΔSOC>0 is considered impossible. All impossible transitions set to have infinite cost. For other possible connections, transitions cost is calculated by (1). This procedure is performed for each time '*t*'. For each state at '*t*',

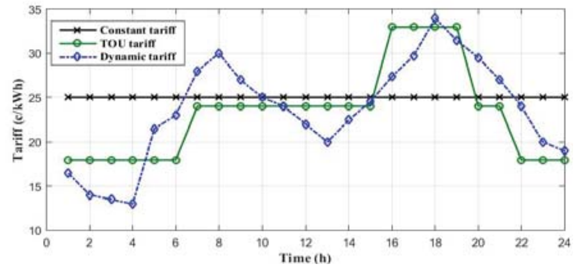

Fig. 4. Electricity tariffs

program takes all the states from '*t*-1' to check the possibility of the transition. Again, all impossible transitions set to have infinite cost. Total cost for each possible connection is the sum of the transition cost and the total cost at the state in '*t*-1'. This procedure is repeated for each state at '*t*' considering all the states at '*t*-1', and finally the transition with minimum cost is chosen as the best path to reach the current state in that time. The DP algorithm ends at '*t*=*T*', in which the SOC of the BESS returns to its initial value, since the final storage level needs to be equal to the initial value. The last state carries with itself all the previous choices made at each state, and identifies the optimal path for BESS operation and the grid power.

III. Simulation and Results

A typical house (H1) in Queensland with maximum load of 3 kW [3] and two homes (H2 and H3) from Ausgrid database [13]are selected as the test systems to validate the effectiveness of the presented HEM unit. Each home is equipped with a rooftop PV and a lead-acid BESS with nominal life cycle of 3000 and initial values (C_{BESS}) of 400 $/kWh. Hourly load and PV generation data are shown in Fig. 3. In this study three different types of electricity retail prices are taken into account; constant, TOU, and dynamic tariff. Constant tariff is a flat rate price with the same value at each hour of the day. TOU tariff consists of an off-peak price period, two shoulder times and one peak price time period. Dynamic tariff with hour-by-hour price is also utilized to study the economic impact of storage under hourly based tariff. The values for constant and TOU tariffs are taken from website of Origin Energy, a local electricity retailer, and dynamic tariff model is adapted from [14] and are plotted in Fig. 4. Furthermore, two FIT rates, namely 6 c/kWh and 44 c/kWh, are utilized in this study. It is worth mentioning that in Queensland State and almost all states of Australia, FIT rate of 44 c/kWh has been closed and only FIT rate of 6 c/kWh is available for new PVs installers. However, households and businesses who have applied before the deadline (July 2012 in Queensland) can still be benefited from the generous FIT rate of 44 c/kWh. HEM is done considering two charging/discharging strategies for BESS; *constrained operation*, i.e., only solar charging is allowed, and *flexible operation*, i.e., BESS can be charged from the grid. Also, HEM unit uses δ_{SOC} as 0.01; $SOC(0)$, SOC^{min} SOC^{max} and P^{max}_{Grid} are 0.5, 0.2, 0.8 and 4 *kWh* respectively.

A. HEM Unit with Constrained Operation of BESS

The results obtained by the proposed HEM technique are shown in Table I. The management is done by considering

TABLE I. CoEC USING PROPOSED ENERGY MANAGEMENT UNIT

System structure			Pricing model		
			Constant	*TOU*	*Dynamic*
H1	W/O BESS	FIT=6 c/kWh (c)	437.1	436	464.87
		FIT=44 c/kWh (c)	-338.1	-339.2	-310.3
		Spilled PV energy	1.55 (kWh)		
	With BESS	FIT=6 c/kWh (c)	381.77	375.83	397.34
		FIT=44 c/kWh (c)	-395.98	-397.6	-368.21
		Spilled PV energy	0		
H2	W/O BESS	FIT=6 c/kWh (c)	505.24	468.93	522.82
	With BESS	FIT=6 c/kWh (c)	452.45	418.651	464.15
H3	W/O BESS	FIT=6 c/kWh (c)	737.42	647.83	733.55
	With BESS	FIT=6 c/kWh (c)	665.37	579.86	647.98

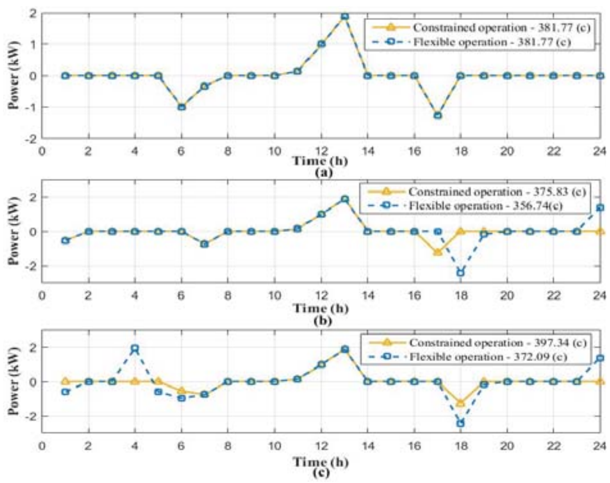

Fig. 3. BESS operation and CoEC for H1 with 5 kWh BESS under (a) constant, (b) TOU, and (c) dynamic tariff

different BESS size for each home under three different EP models and by taking into account two different FIT rates. Total daily CoEC before storage installation is also included in this table to compare the validity of the management model.

As it can be seen form Table I, the value of CoEC is negative for H1 when FIT=44 c/kWh under all tariffs, before and after BESS installation. In other words, the amount of money received by the solar system owner from exporting energy into the grid is greater than the cost of energy usage from the grid, because the rate of 44 c/kWh is much higher than the grid EP, even at peak values. Therefore, costumers receiving payments at a rate of 44 c/kWh can make good use of this generous incentive and maximize their income by selling as much of their solar electricity back to the grid as possible. The profit is increased by installing storage system, however, it does not make economic sense to install BESSs. So, we did not run HEM unit under FIT rate of 44 c/kWh for H2 and H3. In case of FIT=6 c/kWh, daily energy consumption cost is significantly reduced after storage installation for all homes. Thus, installing BESS will always be cost-effective in all tariff schemes. For H1, large reduction occurs under dynamic tariff (about 15%) in comparison to constant and TOU tariffs (13% and 14%, respectively). This is the case for H2 and H3, too. Hence, it is evident that for PV investors under dynamic tariff,

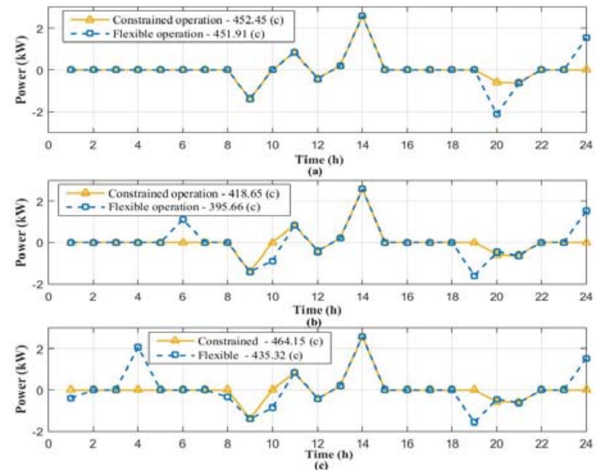

Fig. 4. BESS operation and CoEC for H2 with 5 kWh BESS under (a) constant, (b) TOU, and (c) dynamic tariff

installing BESSs will be of great monetary advantage to shave their electricity bills. Furthermore, obtained results indicates that TOU tariff leads to a lower expenditure on grid electricity and brings about more profit compare to other two tariff models. Additionally, Table I reveals that utilizing BESSs will prevent curtailment of solar energy. The voltage problems in distribution network limits the amount of power injection to the grid, resulting in energy spillage in absence of BESS. BESSs whereas, can store this spilled energy, thereby adding value to the PV owner.

The hourly BESS power schedule and and daily cost for different price structures with a FIT=6 c/kWh are depicted in Figs. 5, 6 and 7 for H1, H2 and H3, respectively. The positive and negative values means charging and discharging, respectively. As expected, under all tariff models, BESS is charged as much as possible with PV power during peak radiation hours as it is the only option for optimal operation. BESS is discharged at load peak periods or price peak hours. HEM unit serves the load firstly by the PV power and the BESS is employed when PV generation is not sufficient or zero. As SOC of the BESS should return to its initial value, the management unit prevents fully discharge of the battery so that flexibility and efficiency of HEM unit for the next day is preserved.

B. HEM Unit with Flexible Operation of BESS

Under flexible operation strategy, BESSs are allowed to flexibly charged/discharged with the grid. Results obtained for two operation strategies are compared in Figs. 5, 6 and 7. BESS action has changed with flexible operation strategy under all tariff models, as it can be fully discharged during the day, because the grid can charge up the BESS later at 24 p.m. when the grid EP is low. Also, flexibility and freedom of BESS operation allows it to get charged/discharged more frequently in comparison to the constrained method, especially under dynamic tariff, accordingly save more on household energy costs. In fact, difference between peak and off-peak prices is utilized more effectively by the HEM unit under dynamic tariff. As results show, the flexible operation of BESS is

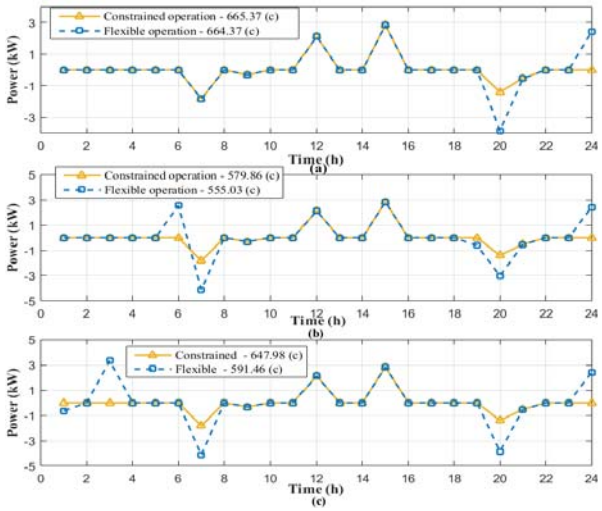

Fig. 7. BESS operation and CoEC for H3 with 8 kWh BESS under (a) constant, (b) TOU, and (c) dynamic tariff

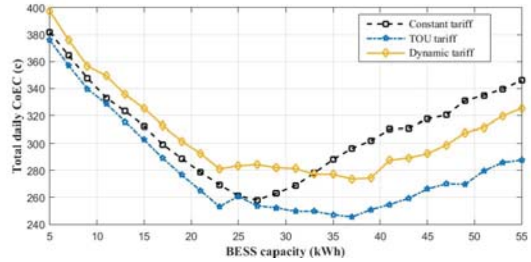

Fig. 8. Impact of BESS size on CoEC for H1 with constrained operation

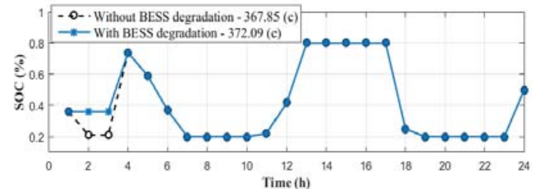

Fig. 9. Impact of BESS degradation for H1 with flexible operation

preferable than the constrained operation as it allows owner to charge BESS using cheap, off-peak grid electricity in order to serve load during peak pricing times, thus cuts energy consumption cost.

C. Impact of BESS Size and Degradation

As shown in Fig. 8, more profit is obtained with higher capacity of BESS due to decrease in the energy usage from the grid. The higher capacity of BESS will enable owner to store more PV generation during sunshine hours, allowing to use it during peak hours. However, at a certain point increasing capacity of BESS is not profitable any more, as further growth of BESS capacity will result in rise of daily CoEC. This point depends on the tariff structure. Fig. 9 shows SOC variation for H1 under dynamic tariff. The scheduling with the consideration of BESS degradation changes more slowly, since it prevents BESS from large cycling events, which is favourable for the battery life. Also, it results in slightly higher cost.

IV. Conclusions

This paper presents a HEM model based on DP algorithm for optimal scheduling of residential grid connected PV-BESSs over the day, considering degradation of BESS. The objective is to analyse energy bill minimization considering various tariff structures. In addition, two charging/discharging strategies for the operation of BESSs, namely constrained and flexible, are considered. Simulation results indicates that there is no economic incentive for customers with FIT=44 c/kWh to install BESSs. Also, flexible operation of BESS is more beneficial and effective, specifically under dynamic tariff. Furthermore, residential customers who have solar PVs and are planning to install BESSs will benefit economically by switching to the TOU tariff. The proposed HEM unit can be implemented in existing homes to manage PV-BESS systems to reduce the cost of electricity consumption and is a reliable solution for price-sensitive customers who want to control their electricity bill and reduce carbon footprint at the same time.

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