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Energy Economy of Households With Photovoltaic System and Battery Storage Under Time of Use Tariff With Demand Charge

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ABSTRACT Power utilities are introducing cost-reflective tariffs, such as a time of use tariff to incentivise electricity use during off-peak periods, some of which include a demand charge during peak periods. The uptake of such tariffs depends on their economic benefits compared to other tariffs. The impact of such emerging tariffs on the household energy economy has not been widely investigated in the South Australian context. This research analyses the energy cost of grid-connected homes with photovoltaic (PV) systems under a time of use tariff with demand charge, recently introduced in South Australia. First, an optimization problem is formulated to minimize the annual household energy cost under a time of use tariff with demand charge, which is also applicable to other tariffs. Then, four types of South Australian PV-installed households are analysed with various battery energy management strategies and tariffs. The results show that a time of use tariff with demand charge can deliver savings in household annual energy cost, which can be further increased using the most appropriate energy management strategy for each tariff. Another key finding is that with battery storage, the time of use tariff with demand charge can reduce the peak load on the distribution feeder by 35% compared to the ordinary time of use tariffs.

INDEX TERMS Battery energy management strategies, battery energy storage, energy cost, optimization, renewable energy sources, solar photovoltaic system, time of use tariff with demand charge.

I. INTRODUCTION

With the increase in electricity prices, there is a trend to move towards more cost-reflective tariff structures around the world [1]. It is expected that half of the South Australian homes would be subject to cost-reflective tariffs by 2025 due to the introduction of smart meters, which are mandatory for the implementation of cost-reflective tariffs [2], [3]. As a part of regulatory control, from 1 July 2021, all customers with smart meters in South Australia (SA) will be moved to the time of use tariffs. Such energy pricing schemes aim to encourage energy consumption at times of low demand while discouraging energy consumption during peak demand periods. Therefore, these tariffs have the potential to reduce stress on the electricity grid by reducing peak demand [4], [5]. The clear benefit is increasing network utilization, which has the long-term benefits of decreasing electricity costs for customers. Various cost-reflective tariffs, such as time of use tariff with demand charge ($ToUD$) and real-time market-based electricity tariffs, are now becoming more feasible with the introduction of smart meters [6], [7]. The impacts of such cost-reflective tariffs on South Australian household energy costs have not been analysed in any literature to date. In SA, where nearly 40% of the homes have solar photovoltaic (PV) systems installed [8], such tariff structures are likely to impact household energy cost given the high PV generation during the mid-day low-demand period. Recently, there were a few occasions when PV-generated energy met the entire South

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Australian load demand for certain time periods [9]. To the best of the authors' knowledge, such instances have not been recorded in other parts of the world, which provides the rationale to conduct a study with such tariffs in SA. In fact, among all Australian states, SA has a unique hourly load profile with the lowest demand occurring in the middle of the day [10]. However, exporting excess PV-generated energy to the grid during the middle of the day may not be the most cost-effective option for households, considering the decreasing feed-in-tariff (*FiT*) due to lowering middle-of-the-day pool prices. This provides a rationale for installing battery energy storage systems in South Australian households with existing grid-connected PV systems. Although the battery cost is still perceived to be high, the progressive reduction in battery cost over the past decade [11], [12], and battery size optimization can lead to an overall reduction in the energy cost of PV-installed homes.

In contrast to previous studies that examined electricity costs of households with PV and battery under standard/flat tariffs [13], [14], this study aims to investigate the impact of time of use tariff with demand charge on electricity cost. The time of use tariff with demand charge (*ToUD*) reflects the consumer's contribution towards the peak demand cost [5]. Typically, this tariff includes additional demand charges and is based on the consumer's peak demand during a designated time period (high-demand period) of any day over a billing cycle. Studies have shown that cost-reflective tariffs could be financially beneficial for a certain category of consumers, but not for others [15]. In addition, the complexity of such tariffs makes them difficult to understand. Consequently, consumers may choose other uneconomical tariffs that could potentially contribute to energy poverty, that is, compromising daily energy needs to avoid paying high bills [16], [17]. Therefore, it is critical to conduct a thorough cost-benefit analysis of such tariffs for household customers.

To date, a large amount of research has focused on the minimization of the energy cost of residential houses under flat tariffs or variable tariffs such as time of use tariff [18]–[23]. Studies such as [18] have minimized the annual energy cost of net-zero energy homes using the optimal battery size for flat tariffs. Another study [19] determined the potential savings in energy cost achieved through battery storage and PV systems under flat tariffs. Reference [20] modelled an optimal energy cost control of grid-connected homes with PV and battery under a time of use tariff scheme. Similarly, studies [21], [22] have minimized the energy cost of the household through optimal sizing of PV and battery for time of use tariffs. Another study [23] has explored battery energy management strategy to further minimize energy cost for the time of use tariff. However, there has been no detailed investigation of the impact of demand charge, which is becoming a common feature of the time of use tariffs around the world for residential and commercial buildings [24].

A limited number of studies such as [7], [25]–[32], have attempted to investigate the demand charge along with variable tariffs. A study [25] investigated the possibility of reducing energy cost based on various *ToUDs,* using PV systems and found that the PVs are uneconomical to reduce demand tariffs in Iran. A recent study [26] analysed the *ToUD* to minimize the home energy cost using an optimal charging/discharging strategy for battery storage. However, it did not include any PV systems and did not consider the optimal battery size. Another study [27] used both PV and battery storage to reduce demand charges, but it did not investigate the optimal size of the battery and its energy management strategies, which are important considerations due to the high cost of battery storage, especially in the case of residential homes. Reference [28] has determined an optimal size of the battery storage along with PV systems to minimize the energy cost under demand tariffs. However, it has not considered any energy management strategy and peak load reduction. In addition, the breakeven point after which it is economical to use a battery with PV system was not studied but recommended in future work. A study [29] examined the energy cost of a single household under real-time pricing and demand charges. However, real-time pricing is not widely used in the Australian residential sector. Another study [30] used a stochastic programming approach to minimize the residential energy cost under *ToUD*. A swarm evolutionary algorithm-based home energy management system was developed in [31], which controls multiple operations of home appliances and battery charging/discharging schedules to minimize the energy cost under *ToUD*. However, the approaches used in [30], [31] are computationally demanding and difficult to use in residential homes with limited processing devices. A similar study [32] focused on minimizing the energy cost by changing the load schedule according to the demand charge, which may not always be possible for residential homes. Another reference [7] considered the *ToUD* for load shifting and peak shaving applications for a residential consumer with battery storage. However, the effect of battery cost and PV size variation on the household energy cost was not investigated.

The above literature review highlights that there has not been much comprehensive study on the impact of *ToUD* on the energy cost of residential PV-homes. To the best of our knowledge, no study comparing *ToUD* with other tariffs has been carried out for South Australian grid-connected residential homes. The present research explores, for the first time, the impact of *ToUD* on the annual energy cost of South Australian grid-connected PV-installed homes. In doing so, this study investigates optimal residential battery sizing under such tariffs and explores alternative battery energy management strategies that can further minimize the household energy cost under *ToUD* tariff schemes currently available in SA. An optimization problem is formulated, which is then solved using the genetic algorithm [33] to determine the optimal battery size and annual energy cost of the household under *ToUD*. The optimization problem is developed in a way that is applicable to a range of tariff structures. Four types of South Australian households with various PV sizes are investigated for two current *ToUD*s and compared with an existing *ToU* and an existing flat tariff. The breakeven point after which the use of a battery with PV system is economical is also investigated. Therefore, the key contributions of the paper include the following:

1) Develop an objective function to minimize the energy cost of households with PV and battery for the time of use tariff with demand charge. It is developed in a generic manner so that it can be applied to other tariff schemes as well.
2) Determine the efficacy (cost-benefit) of time of use tariff with demand charge for South Australian households and the impact of various energy management strategies on energy cost.
3) Determine how a time of use tariff with demand charge compares with other tariffs in terms of managing the peak load on distribution feeders.

The paper has been organized into nine sections. Section II provides an insight into system modelling. Section III presents the mathematical formulation of the objective function and Section IV describes various energy management strategies. Section V describes the algorithm. Section VI presents a discussion of the results and Section VII discusses the limitations of the study. Sections VIII and IX present the conclusions and future work respectively.

II. SYSTEM MODELLING

Nearly 40% of homes in SA have rooftop PV panels [8]. Despite the reverse power flows and overvoltage issues caused by this high PV penetration in low-voltage networks, residential solar PV installation is growing rapidly [34]. Owing to such high PV penetration, this study assumes that PV systems are already installed in the studied houses. Therefore, the cost of PV installation is not considered. The annual energy cost of these households can be minimized by installing optimally sized battery storage. Fig. 1 shows a battery connected to a PV system. A battery converter may not be required if the PV system has a battery-ready inverter. Using the notations shown in Fig. 1, the power balance equation at the point of common coupling can be written as:

$$P_{PV}(t) + P_{imp}(t) + P_{Bdis}(t) = P_{Ld}(t) + P_{exp}(t) + P_{Bch}(t) \tag{1}$$

$$P_{imp}(t) \times P_{exp}(t) = 0 \tag{2}$$

$$P_{Bch}(t) \times P_{Bdis}(t) = 0 \tag{3}$$

Equation (2) indicates that at any instance of time, power can be either exported or imported to/from the grid, that is, exports and imports cannot occur simultaneously. Likewise, equation (3) shows that charging and discharging of the battery cannot take place simultaneously. Few other constraints related to battery operation and grid energy are described in the following subsections.

A. BATTERY OPERATING CONSTRAINTS

This study has considered a lithium-ion battery for the analysis because of its suitability and wide availability for residential homes. The state of charge equations are given in the Appendix as (A.1) and (A.2) [13], [18]; therefore, only a few operating constraints are discussed here. The conversion losses associated with the battery and inverter are included in the equations.

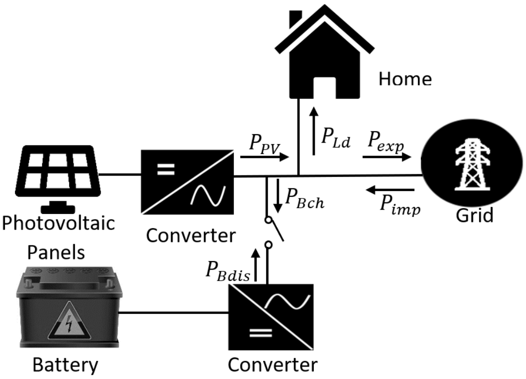

FIGURE 1. System configuration.

1) The energy discharged by the battery is used only to meet the household load demand. The battery can be charged only from the PV, that is, battery charging from the grid is not allowed.
2) The battery is charged or discharged only within the battery state of charge (*SoC*) limits.
3) The charging and discharging efficiencies are considered to account for the losses.
4) Battery operations follow the power balance equation (1), and constraints (2) and (3).

For simplicity, the study does not include the degradation of the battery and PV panels; however, it can be incorporated using a degradation factor in the existing model.

B. GRID CONSTRAINTS

The mismatch between load and PV generation patterns is met by importing/exporting energy from/to the grid. There are some constraints related to energy exchange with the grid, such as the export limit. The maximum export limit for single-phase houses in SA is 5 kW, which is considered in this study [35].

PV owners have to pay some annual energy cost to the utility due to the energy exchange with the grid. This energy cost depends on the tariffs at which energy is exchanged. Therefore, the following section describes the tariffs under investigation and their relationships with the export/import of energy.

III. ENERGY COST CALCULATION UNDER TIME OF USE TARIFF WITH DEMAND CHARGE

Unlike others, this study aims to minimize the annual energy cost for PV-installed households under the time of use tariff with demand charge (*ToUD*). Time of use (*ToU*) tariffs cost less during off-peak periods and more during peak periods [23], [36]. Fig. 2(a) shows the retail prices RP_p, RP_o and

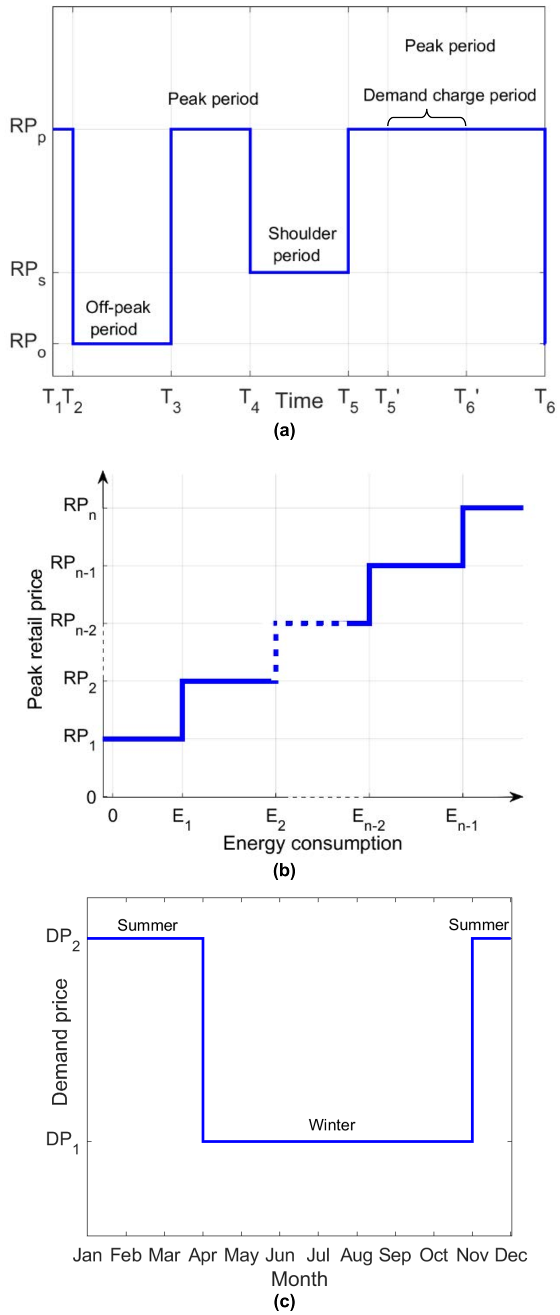

FIGURE 2. **(a) Time of use tariff with demand charge period, (b) Variation of retail price against energy consumption, (c) Variation of demand price between summer and winter seasons.**

RP_s charged during peak periods (T_1 to T_2, T_3 to T_4, and T_5 to T_6), off-peak (T_2 to T_3), and shoulder periods (T_4 to T_5), respectively. In some tariffs, the retail price during the peak period is not constant; rather, it varies with the amount of energy consumed during a specific period (e.g. a month). Fig. 2(b) shows an example of a variable peak-period retail price, where the price increases in steps with an increase in the amount of energy consumed. The variable retail price of electricity is also known as a step tariff or peak usage charge [37].

The demand charge period (T_5' to T_6') shown in Fig. 2(a) is the period when consumers pay an additional charge based on the level of power consumption. The higher the power consumption, the higher the demand charge. In the USA, the demand charge is based on the average power demand over a period of time [24]. In SA, it is based on actual maximum demand (kW) measured over a half-hour interval during the demand charge period on any day of the month [38]. Two types of demand prices are applied based on the season, as shown in Fig. 2(c), where summer and winter last for five and seven months, respectively. Because the highest peak demand occurs in summer, its demand prices are higher than those in winter. *ToUD* is also known as a residential demand tariff or a capacity tariff [5].

Based on the descriptions given above, the electricity cost under time of use tariff with demand charge EC_{ToUD} can be calculated as the sum of four components:

1) Off-peak-period electricity cost based on off-peak *ToU* tariff (EC_o)
2) Shoulder-period electricity cost based on shoulder *ToU* tariff (EC_s)
3) Peak-period electricity cost based on peak *ToU* tariff (EC_p)
4) Demand charge paid during the demand charge period (DC)

$$EC_{ToUD} = EC_o + EC_s + EC_p + DC \tag{4}$$

For time of use tariffs without any demand charge (*ToU*), the last term of (4) is zero, and for flat tariffs, each of the last three terms is zero, where EC_o is the flat price of electricity per kWh for the entire day. The four components of the electricity cost are described below. Note that the demand price varies with the month (see Fig. 2(c)). Therefore, the electricity cost components are calculated on a monthly basis and then added to arrive at the annual cost.

The monthly electricity cost for the off-peak period EC_{om} mainly depends on the amount of energy consumed during the off-peak period and the corresponding retail price. The energy consumption during the off-peak period in a month m (E_{om}) can be expressed as:

$$E_{om} = \sum\nolimits_{t \in \alpha_m} P_{imp}(t)\Delta t \tag{5}$$

where, $P_{imp}(t)$ is the power imported (kW) from the grid during time period t and can be derived from (1). α_m is a set of time intervals during the off-peak periods in month m and Δt is the length of the time interval (half an hour in this case). The corresponding electricity cost (EC_{om}) in month m can be written as:

$$EC_{om} = RP_o \times E_{om} \tag{6}$$

If there are five hours of off-peak periods in a day, the number of half-hourly time intervals in the set α_m is 10 per day.

Similar to the off-peak period, the electricity cost during the shoulder period can be written as:

$$EC_{sm} = RP_s \times E_{sm} \tag{7}$$

where energy consumption E_{sm} depends on the power imported during the shoulder period β_m in month m. Here, β_m represents the set of time intervals during the shoulder period.

The peak-period electricity cost depends on the amount of energy consumed during the peak period and peak period retail prices. The energy consumption during the peak period in month m (E_{pm}) can be expressed as:

$$E_{pm} = \sum\nolimits_{t \in \gamma_m} P_{imp}(t)\,\Delta t \tag{8}$$

where γ_m is a set of time intervals during the peak periods in month m. Using Fig. 2(b), the peak-period electricity cost (EC_{pm}) in month m can be calculated as follows.

$$EC_{pm} = \begin{cases} E_{pm} \times RP_1; \qquad E_{pm} \le E_1 & (9) \\ \sum\nolimits_{i=1}^{k-1} (E_i - E_{i-1})\,RP_i + \left(E_{pm} - E_{k-1}\right)RP_k; & \\ E_{k-1} < E_{pm} \le E_k \qquad (k = 2, 3 \ldots n) & (10) \end{cases}$$

Here $E_0 = 0$, and $RP_1, RP_2 \ldots RP_n$ are the retail prices paid for consuming energy under the respective consumption slabs ($E_1, E_2 \ldots E_n$), as shown in Fig. 2(b). It is clear that if there is only one slab or the energy consumption is up to E_1 then (9) calculates the electricity cost; otherwise, (10) calculates the electricity cost, where the first term represents the cost of energy for all slabs except the last one and the second term represents the cost of energy for the remaining portion of the last slab.

Unlike off-peak, shoulder and peak-period electricity costs, which depend on the energy consumed, the demand charge depends on the power demand. The maximum imported power during the demand charge period in month m (P_{pm}) can be expressed as:

$$P_{pm} = \max_{t \in \delta_m} \left(P_{imp}(t)\right) \tag{11}$$

where δ_m is a set of time intervals during the demand charge period in month m. The corresponding demand charge (DC_m) in month m can be expressed as:

$$DC_m = DP_m \times m_d \times P_{pm} \tag{12}$$

where DP_m is the demand price for month m and m_d is the number of days in month m.

Thus, using (6), (7), (9), (10) and (12), the annual electricity cost for the time of use tariff with demand charge EC_{ToUD} can be calculated as follows:

$$EC_{ToUD} = \sum\nolimits_{m=1}^{12} (EC_{om} + EC_{sm} + EC_{pm} + DC_m) \tag{13}$$

Because the studied houses already have rooftop PV systems installed, the house owner earns revenue by exporting excess PV energy to the grid at the feed-in-tariff (*FiT*). The earned revenue (*RE*) can be expressed as [18]:

$$RE = FiT \times \sum\nolimits_{t \epsilon T} P_{exp}(t)\,\Delta t \tag{14}$$

where $P_{exp}(t)$ represents the power exported to the grid for time period t and T is a set of half-hourly time intervals in a year. Note that $P_{exp}(t)$ can be derived using (1). Considering the revenue earned for exporting excess PV energy and the annual electricity cost paid for importing energy under the *ToUD* scheme, the net annual electricity cost (EC_{net}) paid to the utility can be written as [18]:

$$EC_{net} = EC_{ToUD} - RE \tag{15}$$

Initially, in SA, the government-mandated and customers subsidised attractive *FiT*s were offered (even more than the retail price of electricity [39], [40]), which resulted in a high uptake of PV systems. The *FiT*s have experienced drastic reductions in recent years [41]. Currently, the maximum *FiT* is $0.17/kWh for the flat tariff [42] and $0.12/kWh for the *ToUD* [6], while the flat retail price of electricity after discounts is approximately $0.38/kWh [43]. Due to the reduction in *FiTs*, the household revenue for exporting energy to the grid has decreased substantially. For this reason, PV owners are looking for alternatives such as battery storage to minimize the net annual electricity cost. The installation of battery storage in households with PV can significantly reduce the exchange of energy with the grid, especially during the peak and demand charge periods, and, consequently, reduce the net annual electricity cost.

In Australia, most lithium-ion batteries have a 10-year warranty [44]–[46]; therefore, the maintenance cost of the battery is not considered in this study. It is assumed that the initial capital cost of the battery (CC_b in $/kWh) is sourced from a financial institution at an interest rate of *int* for N years, where N is the life span of the battery. Note that the initial capital cost of the battery includes the installation cost. Therefore, the battery annual payment rate (A_b in $/kWh/yr) paid to the financial institution reflects the remaining cost of the battery. Mathematically, the battery annual payment rate can be expressed as [14]:

$$A_b = CC_b \times CRF\,(int, N) \tag{16}$$

where, *CRF* is a well-known capital recovery factor written as [13]:

$$CRF = \frac{int\,(int + 1)^N}{(int + 1)^N - 1} \tag{17}$$

Therefore, the overall annual energy cost for household EC_a can be expressed as the sum of the net annual electricity cost EC_{net} and the battery payment for the respective battery capacity C_b(kWh). Thus, the objective function can be formulated using (15) and (16):

$$f\,(C_b) = EC_a = EC_{net} + C_b A_b \tag{18}$$

Here the term EC_{net} expressed by (15) is evaluated in such a way that it satisfies all the constraints discussed in

Sections II and III. Note that this objective function can be applied to other tariff schemes such as flat and *ToU* tariffs without demand charges by making the non-applicable terms in (13) zero. For given patterns of PV generation and load, tariff structure, interest rate, battery cost and its life span, the annual energy cost depends only on the battery size. The above optimization problem is solved considering the load and PV generation patterns, the cost equations presented earlier in this section for the import and export of energy, and the *SoC* equations presented in Appendix.

Note that the optimal battery size and, consequently, the annual energy cost also depends on the energy management strategy used for charging/discharging the battery storage. The next section describes different types of energy management strategies that can be deployed.

IV. ENERGY MANAGEMENT STRATEGIES

Four energy management strategies (*EMS*), *S1*−*S4*, based on battery discharge periods, are investigated in this study with the aim of maximizing the benefits of battery storage. The discharging period is selected based on various factors, such as the peak period, demand charge period, and seasonal demand prices. Figs. 3(a) and 3(b) show the battery discharge periods (indicated by double-headed arrows) for two different time of use tariffs with demand charges ($ToUD_1$ and $ToUD_2$). For example, there is no time restriction on battery discharging in Strategy 1 (*S1*), so the battery can be discharged at any time of the day. However, in Strategy 2 (*S2*), the battery can be discharged only within a specified time period. The x-axis shows the 24-hour period starting at 06:00. Here, only the first two strategies are shown, while the last two strategies are obtained by a combination of strategies 1 and 2.

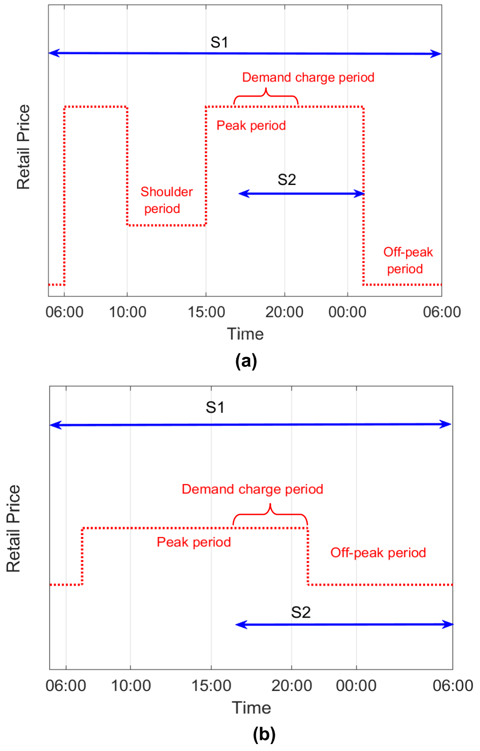

FIGURE 3. **(a) Battery discharge periods for $ToUD_1$, (b) Battery discharge periods for $ToUD_2$.**

When the PV generation exceeds the load demand, the surplus PV power is used to charge the battery if its state of charge (*SoC*) is less than the maximum permissible *SoC*; otherwise, the surplus PV power is exported to the grid subject to the maximum export limit imposed by the power utility. If the PV generation is equal to the load demand, the occurrence of which is very rare, no action is taken, and the battery *SoC* remains the same. If the PV generation is less than the load demand ($P_{PV} < P_{Ld}$), the battery needs to be discharged to meet the load demand. A flowchart illustrating the four alternative energy management strategies deployed to discharge the battery is shown in Fig. 4. In strategy 1 (*S1*), the battery can be discharged at any time when $P_{PV} < P_{Ld}$ if the battery *SoC* is above the minimum permissible *SoC*; otherwise, the shortfall is met by importing energy from the grid.

As shown in Figs. 3(a) and 3(b), in strategy *S2*, the battery is allowed to discharge only from the start of the demand charge period until a specified time ($\delta_m + \omega_m$). The primary aim is to reduce the cost due to demand charges during the peak period in addition to reducing the peak period energy costs. This condition is implemented in the flowchart shown in Fig. 4. The time until which the battery can be discharged may vary according to the tariff structure. Fig. 3(a) shows that the time until which the battery is discharged is 1am ($\omega_m = \gamma_{m1}$) for $ToUD_1$, because the peak period ends here. This is done to minimize the import of energy at peak period charges, which are generally much higher than the off-peak period charges [32]. However, for $ToUD_2$, the specified time is extended until 6am ($\omega_m = \alpha_{m1}$) as shown in Fig. 3(b). This is done because, after this time, the sun generally rises, and the PV energy can partially or fully serve the load.

Each of the strategies *S3* and *S4* has an additional seasonal conditional block, as shown in Fig. 4. In strategy *S3*, if the

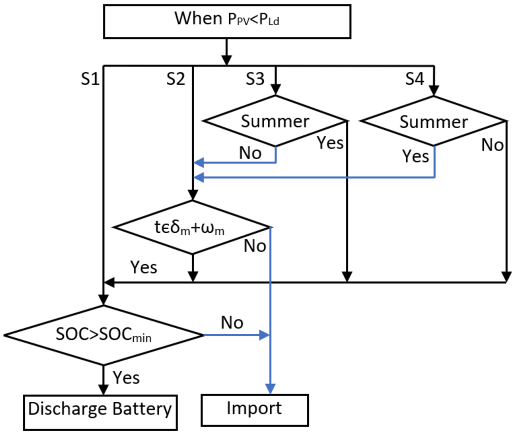

FIGURE 4. **Flowchart of battery energy management strategies.**

time period lies in summer, strategy *S1* is followed while *S2* is followed in winter. Note that the duration of winter in SA is seven months and the sunlight periods are shorter than in summer. Therefore, in *S3*, the battery discharge period is restricted in winter by utilizing *S2* to provide sufficient time to charge the battery. Strategy *S4* is the opposite of *S3* and aims to reduce the cost incurred due to the high summer demand price, which is significantly higher than the winter demand price. Therefore, in *S4*, to minimize the summer demand charges as a priority, strategy *S2* is followed during summer, while *S1* is followed in winter.

In all the energy management strategies, the battery voltage is assumed to remain more or less constant between the maximum and minimum state of charge. The discharging periods for both tariffs ($ToUD_1$ and $ToUD_2$) are summarized for all the *EMSs* in Table 1. All strategies are investigated and compared from various perspectives in Section VI.

TABLE 1. Battery discharging periods for various energy management strategies.

Strategy	Discharging Period
S1	Any time
S2	5pm-1am (*ToUD₁*) and 4pm-6am (*ToUD₂*)
S3	*S1* (Summer) + *S2* (Winter)
S4	*S2* (Summer) + *S1* (Winter)

V. ALGORITHM

The computational steps to minimize the annual energy cost for PV-installed households under the *ToUD* scheme are as follows:

1) Select an *EMS* (*S1*-*S4*) from Fig. 4 and calculate import and export power using (1) and (2).
2) Compute annual electricity cost for *ToUD* using import power using (5)–(13).
3) Compute export revenue using (14) and the net annual electricity cost using (15).
4) Use objective function in (18) to minimize the annual energy cost with a genetic algorithm for an optimal battery capacity C_b.

VI. RESULTS AND DISCUSSION

The annual energy costs of four types of grid-connected PV-installed households, located in Adelaide, the capital city of SA, are analysed. They are classified into four categories based on their energy consumption and the number of people per household as shown in Table 2 [47]. The annual half-hourly load pattern of a typical low energy consumption household (8.4 kWh/day) is shown in Fig. 5, which is scaled up for other household types. For the low consumption household, the peak load observed is 1.135 kW, averaged over a period of half an hour. The processing needed to obtain the household load profile based on household type is given in [48]. The houses are assumed to have no controlled loads.

Hourly PV generation data is obtained from the renewable ninja website [49] (as described in [48]). To match the half-hourly interval of the load data, an average of two successive PV generation data points is taken as the PV generation in the middle of the hour. A total system loss of 10%, tilt of 35° and north-facing orientation are considered in creating the PV generation pattern. The effect of temperature is included in the generated PV power. Fig. 6 shows the annual half-hourly power output of a 1-kW_p PV system. PV generation may vary year-to-year depending on changes in solar irradiance and temperature profiles. Considering that these factors will not change drastically in the upcoming years, the year-to-year variations in the PV generation are not considered.

TABLE 2. Classification of various households.

Household type	No. of people	Consumption per day (kWh)
Low	1	8.4
Medium	2-3	13.0
High	4-5	16.9
Very High	5+	21.0

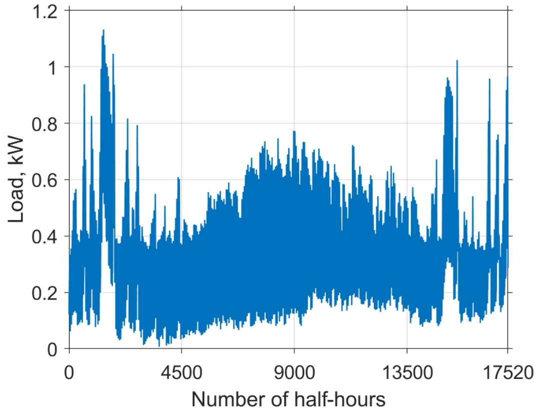

FIGURE 5. Load pattern of low energy consumption household.

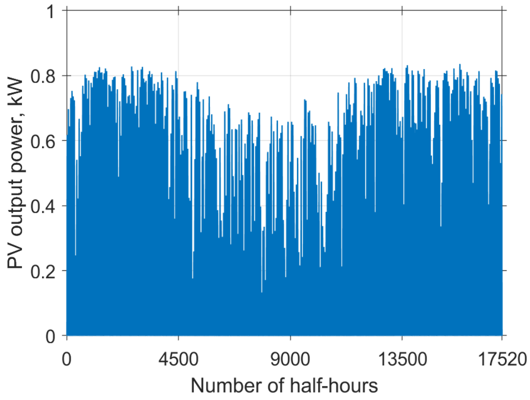

FIGURE 6. PV output power generation pattern per kW_p over a year.

Four existing South Australian tariffs are used for the analysis: time of use tariff (ToU_1), time of use tariffs with demand charges ($ToUD_1$ and $ToUD_2$), and flat tariff (see Table 3 and 4 for details). All four energy management strategies discussed in Section IV are investigated and compared. The battery

TABLE 3. Electricity prices under various tariffs [6], [50]–[52].

Tariffs	Peak ($/kWh)		Demand Charge ($/kW)		Off-peak ($/kWh)	Shoulder ($/kWh)	Second shoulder ($/kWh)	FIT ($/kWh)	Supply charge
ToU_1 [50]	17-21pm Summer	17-21 pm Winter	--	--	10-15pm	6-10am,15-17pm, 21pm-1am	1-6am	All time	Daily
Price	1.25	0.36	--	--	0.08	0.20	0.12	0.060	1.10
$ToUD_1$ [6]	0-1am, 6-10am,15pm-0am		17-21pm Summer	17-21pm Winter	1am-6am	10am-15pm	--	All time	Daily
Price	0.33		0.8427	0	0.165	0.22	--	0.120	0.7604
$ToUD_2$ [51]	7-21pm		16-21pm Summer	16-21pm Winter	1-7am & 21pm-0am	--	--	All time	Daily
Price	See Table IV		0.4641	0.2292	0.2486			0.102	1.1545
Flat [52]	0.378		--	--	--	--	--	0.120	0.86

TABLE 4. Peak usage rates for energy consumption under $ToUD_2$ [51].

Consumption limit (kWh/month)		Peak usage rates ($/kWh)	
E_1	100	RP_1	0.3724
E_2	333	RP_2	0.3839
E_3	833	RP_3	0.4169
E_4	>833	RP_4	0.4290

discharging periods of these strategies are listed in Table 1 for $ToUD_1$ and $ToUD_2$. For completeness, the discharging periods for ToU_1 are given in Table 7 and Fig. 15 of the Appendix.

The technical and financial parameters of the battery are taken from [18]. A battery capital cost of $440/kWh is used in the analysis, which corresponds to $52/kWh/year battery annual payment rate at a 3% interest rate and 10-year battery life span. This battery cost is achievable, given that batteries are available at a capital cost of $740/kWh [46], [53], and that the SA government pays a battery rebate of $300-400/kWh [54]. Note that the cost of the battery depends on both the energy and power rating costs as explained in [55]. However, most of the residential battery storage in Australia has a maximum charging/discharging rate of 5 kW [56]–[58]. In this study, the same maximum charging/discharging rate of the battery, i.e., 5 kW is considered. The battery capital cost stated above incorporates the power rating cost for a maximum charging/discharging rate of 5 kW, in addition to the energy rating cost. Considering the wide range of battery prices in the market a sensitivity analysis is also carried out in Part D of Section VI for various battery costs. To solve the optimization problem, the genetic algorithm (*ga*) optimization function of MATLAB is used as a solver with '100' generations as the stopping criterion. The various results obtained using above data are discussed as follows.

A. ANALYSIS OF ENERGY MANAGEMENT STRATEGIES

First, a household with high energy consumption and a 5 kW PV system is investigated. Table 5 compares the annual energy costs and corresponding optimal battery sizes for all four energy management strategies *(EMS)* for the four tariff structures introduced in the previous section. It is observed that, for all tariff structures, compared to using the PV system without battery or no PV system at all, the annual household energy cost is reduced when an optimally sized battery is used with the PV system. The energy cost can be further reduced by selecting an appropriate energy management strategy *(EMS)*. For example, when the 5 kW PV system is used with an optimally sized battery under strategy *S1*, the annual energy cost with $ToUD_1$ is reduced by 11.8% compared to using the 'PV only' system. A further reduction of 1.3% is achievable when the battery is used with the *S4* strategy while taking 1am as the discharging end time. Although the overall savings are not high (∼13%), they can be higher for other types of tariffs and for much larger energy-consuming premises such as commercial buildings.

The same *EMS* does not necessarily deliver the lowest energy cost for all tariff structures. *S1* seems to be the most cost-effective strategy for $ToUD_2$, *S2* for TOU_1 with a discharging end time (*DET*) of 6am for both tariffs, and *S4* is the most cost-effective strategy for $ToUD_1$ with a *DET* of 1am. Among all tariffs, $ToUD_1$ is the most cost-effective with and without PV and battery, and *S4* is the most economical *EMS* for it. This result is understandable because $ToUD_1$ has a demand charge only in summer (see Table 3), and *S4* minimizes the energy import from the grid during high demand charge and partial peak period in summer.

B. ANNUAL ENERGY COST VERSUS TARIFFS

Fig. 7 compares the annual energy costs for the four tariffs for all household types with 5 kW PV systems. For each individual tariff, the most cost-effective EMS, as observed in Table 5, is used. The bar graphs in Fig. 7 indicate that $ToUD_1$ incurs the lowest annual energy cost for all household types. Note that the above results are obtained by considering the average half-hourly load consumption of the households. However, in SA, the demand charge is calculated based on the actual peak load, which is higher than the half-hourly average. To address this limitation, a sensitivity analysis of the annual

TABLE 5. Annual energy cost and corresponding optimal battery size for various EMS for high energy consumption household with a 5 kW PV system.

Tariff	DET*	Findings	W/o PV & battery	Only PV	With battery for various energy management strategies			
					S1	S2	S3	S4
$ToUD_1$		Battery size (kWh)	--	--	8	7.8	8	8
	1 am	Annual energy cost ($)	2272	770	679	676	686	**670**
	6 am					688	683	684
$ToUD_2$		Battery size (kWh)	--	--	7.1	6.5	6.5	6.5
	1 am	Annual energy cost ($)	2596	988	**889**	910	902	898
	6 am					892	889	892
ToU_1		Battery size (kWh)	--	--	6	5.8	5.9	5.9
	1 am	Annual energy cost ($)	2966	1823	914	895	893	915
	6 am					**890**	892	912
Flat		Battery size (kWh)	--	--	7	--	**--**	--
	N.A.	Annual energy cost ($)	2650	867	**792**	--	**--**	--

* *DET*-Discharging End Time

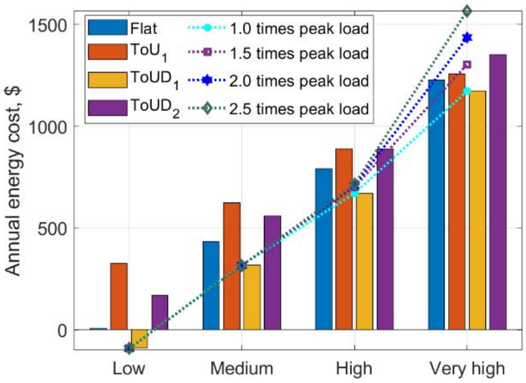

FIGURE 7. Annual energy cost of four households for four tariffs and sensitivity of $ToUD_1$ against peak load.

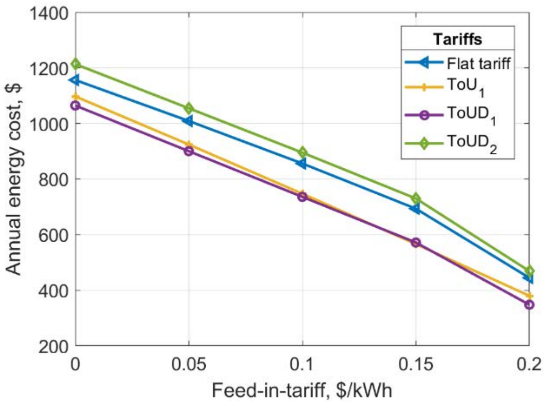

FIGURE 8. Sensitivity of annual energy cost against FiTs of a high consumption household for four tariffs.

energy cost against the peak load for $ToUD_1$ is shown by the dotted line graphs in Fig. 7. The results show that $ToUD_1$ is still economical for all types of households, except for the very high consumption household. When the peak load is increased by 2 and 2.5 times, the energy cost incurred for $ToUD_1$ is the highest for a very high energy consumption household, contrary to the results discussed above. Clearly, the cost-effectiveness of $ToUD_1$ for a very high consumption household highly depends on its instantaneous maximum peak load, which can be reduced or controlled by changing the energy consumption behaviours of the house owners during the demand charge period.

Feed-in-tariff (*FiT*) plays a vital role in reducing annual household energy costs. Therefore, a sensitivity analysis of the annual energy cost for a high consumption household with a 5 kW PV system and optimally sized battery has been conducted against *FiTs* for the four tariffs (see Fig. 8). It shows that the annual energy cost for $ToUD_1$ is the lowest among all four tariffs for a large range of *FiTs*. However, ToU_1 has the potential to incur lower annual energy cost provided higher *FiTs* ($0.10–15/kWh) are offered with the existing tariffs.

C. OPTIMAL BATTERY SIZE VERSUS PV SIZE

The optimal battery sizes for the four types of considered households have been determined for various PV system sizes, as shown in Fig. 9. The most cost-effective tariff ($ToUD_1$) is used in this analysis along with strategy *S4*. The results indicate that for all types of households, the optimal battery size initially increases with the increase in PV size and then becomes more or less constant. For low energy consumption households, Fig. 9 reveals that the optimal battery size is almost constant for PV sizes greater than 4 kW, which means that beyond this capacity, the PVs produce more energy than the total consumption of the household. Therefore, increasing the PV size beyond a certain size would not affect the optimal battery size. However, a larger PV size will increase the energy export (until the export limit is violated) and hence can

TABLE 6. **Battery annual payments and its capital cost.**

Battery annual payment rate Ab ($/kWh/yr)	10	20	30	40	50	60	70	80	90	100
Capital cost of battery ($/kWh)	85	171	256	341	427	512	597	682	768	853

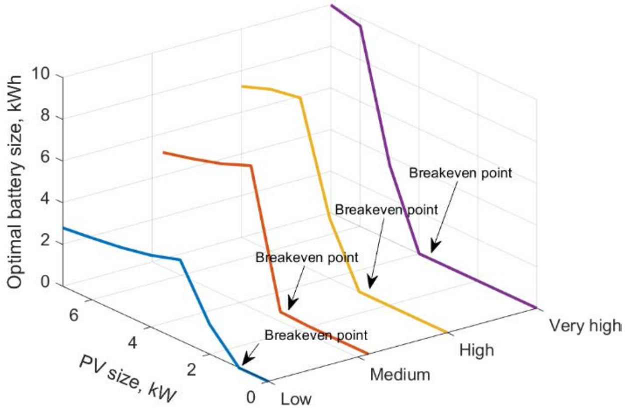

FIGURE 9. **Variation of optimal battery size against PV sizes for four households under (*ToUD*$_1$).**

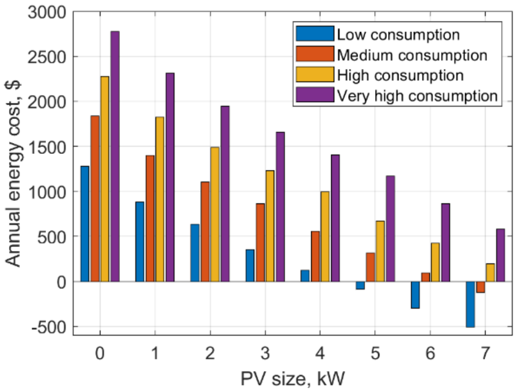

FIGURE 10. **Annual energy cost at various PV sizes for four households with battery.**

potentially reduce the annual energy cost further, as shown in Fig. 10. In Fig. 9, for each household type, the breakeven point for PV size is indicated, after which the combination of PV and battery becomes economically feasible. For example, for a very high consumption household, it is economical to use battery storage with PV sizes above 4 kW.

D. SENSITIVITY ANALYSIS AGAINST BATTERY COST

Table 6 shows the capital costs of the battery for various annual payment rates considering the 3% interest rate and 10-year battery lifespan. All the results presented above were analysed using a battery annual payment rate of $52/kWh/yr, which corresponds to a battery capital cost of $440/kWh. Such a relatively low battery payment is possible in SA because of the state government's battery rebate scheme [54]. The optimal battery size and annual energy cost are directly affected by the battery annual payment rate. Fig. 11 shows the

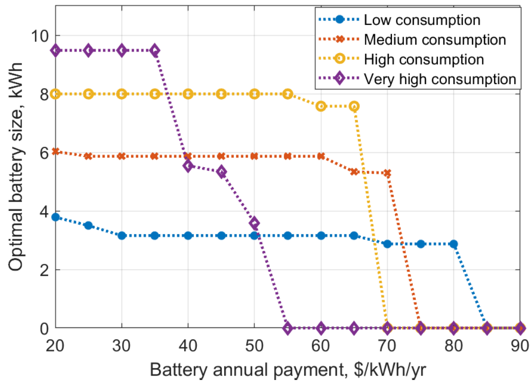

FIGURE 11. **Variation of optimal battery size against battery annual payment rate for four household types with 5 kW PV system.**

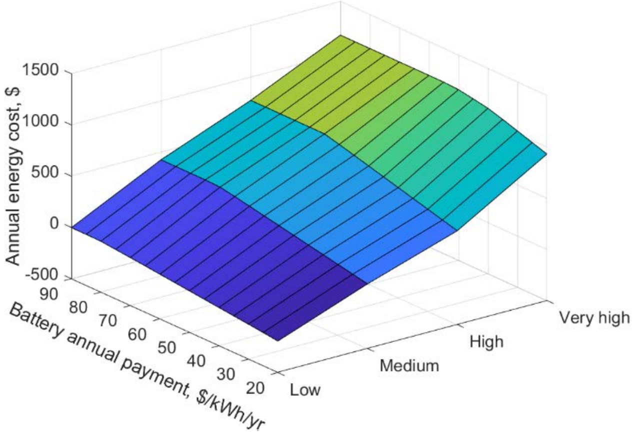

FIGURE 12. **Variation of annual energy cost against battery annual payment rate for four household types under (*ToUD*$_1$).**

variation of optimal battery size against the battery annual payment rate for all types of households when a 5 kW PV system is used. This indicates that the optimal battery size decreases with an increase in the battery annual payment rate and becomes zero at some breakeven point. Note that the battery is economically viable in SA because of the battery rebates; however, for other regions without battery rebates, it may not be beneficial. Fig.12 shows that, for all household types, the annual energy cost decreases with a decrease in the battery annual payment rate. With a lower battery payment rate, a higher optimal battery size is achieved for all households, as illustrated in Fig. 11.

E. PEAK LOAD REDUCTION WITH TARIFFS

Fig. 13 shows the import power of a high consumption household under $ToUD_1$ with and without PV and optimally sized battery as well as for the 'PV only' case. Fig. 13 (a) shows the import power for the last week of January, in which the highest peak demand of the year was observed. This indicates

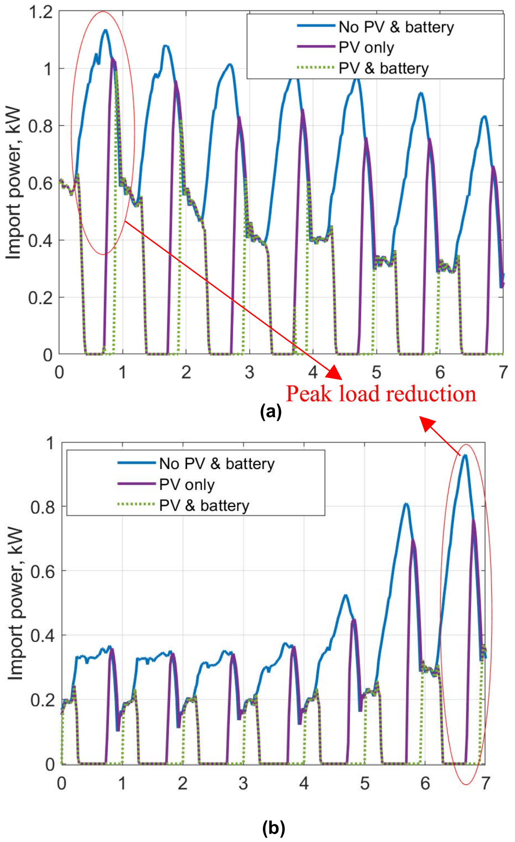

FIGURE 13. **Weekly import power of a high consumption household under ToUD$_1$ for (a) January last week, (b) December second week.**

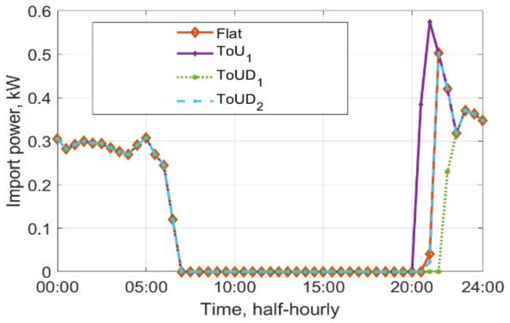

FIGURE 14. **Comparison of import power of a high consumption household for various tariffs.**

TABLE 7. **Discharge periods for various energy management strategies for *ToU*$_1$ [50].**

Strategy	Discharging Period
S1	Any time
S2	5pm-6am (*ToU$_1$*)
S3	*S1* (Summer) + *S2* (Winter)
S4	*S2* (Summer) + *S1* (Winter)

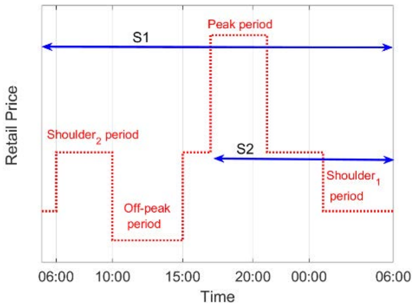

FIGURE 15. **Battery discharge periods S1 and S2 for *ToU*$_1$ [50].**

that the maximum peak demand of the week can be reduced by 0.145 kW (highlighted with a red circle) when a 5 kW PV system is used with an optimally sized battery under $ToUD_1$. Analysing over the whole year it was observed that a maximum reduction of 0.5896 kW in the peak load is achievable in the second week of December, as shown in Fig. 13(b). With this amount of peak load reduction, if there are 2000 households on a feeder, $ToUD_1$ has the potential to reduce peak demand by up to 1.18 MW. This is a clear benefit beyond the meter for using battery storage. Therefore, apart from the reduction in household energy cost, PV systems with battery storage may help the distribution networks in reducing their peak demand. Consequently, utilities can defer the costly infrastructure upgrades required to meet the additional peak load demand incurred in the absence of PV and battery. Fig. 14 compares the import power of a high consumption household with PV and battery for the four tariff structures investigated in this study on the last day of the second week of December. It is found that 35.6%, 12.4%, and 12.4% peak load reductions are achieved when $ToUD_1$ is used as compared to ToU_1, flat tariff and $ToUD_2$, respectively.

VII. LIMITATION OF THE STUDY

As stated previously, the above analysis is carried out using the average South Australian half-hourly household load profile. Some of the households are likely to experience higher instantaneous peak demands than the average on certain days of the year, leading to higher annual energy cost than reported in the results due to the higher demand charges incurred. Using high-resolution load profile data of individual customers can improve the accuracy of the results.

VIII. CONCLUSION

Cost reflective tariffs such as time of use tariffs are finding increasing adoption to encourage electricity use during low-demand periods and discourage usage during high-demand periods. This study has provided, for the first time, an analysis of the annual energy cost of South Australian grid-connected PV homes under time of use tariffs with demand charge (*ToUD*) recently introduced in South Australia. The method relies upon formulating and solving an objective function under *ToUD* to minimize the energy costs of households with given load and PV generation patterns. The proposed objective function is generic and can be applied to determine the household energy costs for other tariff schemes. The results obtained for the four types of households demonstrate that optimally sized battery storage

$$\left.\begin{aligned}
&if\ SOC\ (t-1)+\frac{((P_{PV}(t)-P_{Ld}(t)).\Delta t).\eta_c}{C_b}\leq SOC_{max}\\
&SOC\ (t)=SOC\ (t-1)+\frac{((P_{PV}(t)-P_{Ld}(t)).\Delta t).\eta_c}{C_b}\\
&else\\
&P_{exp}\ (t)\ .\Delta t=((P_{PV}\ (t)-P_{Ld}\ (t))\ .\Delta t)-(SOC_{max}-SOC\ (t-1))\ \frac{C_b}{\eta_c}\\
&SOC\ (t)=SOC_{max}
\end{aligned}\right\}\tag{A.1}$$

$$\left.\begin{aligned}
&if\ SOC\ (t-1)+\frac{((P_{PV}(t)-P_{Ld}(t)).\Delta t)}{\eta_b.\eta_d.C_b}\geq SOC_{min}\\
&SOC\ (t)=SOC\ (t-1)+\frac{((P_{PV}(t)-P_{Ld}(t)).\Delta t)}{\eta_b.\eta_d.C_b}\\
&else\\
&P_{imp}\ (t)\ .\Delta t=((P_{PV}\ (t)-P_{Ld}\ (t))\ .\Delta t)+(SOC\ (t-1)-SOC_{min})\ \eta_b.\eta_d.C_b\\
&SOC\ (t)=SOC_{min}
\end{aligned}\right\}\tag{A.2}$$

can reduce the annual energy cost of South Australian grid-connected PV-homes under *ToUD*. One of the two *ToUDs* considered in this study is found to be the most cost-effective among all analyzed tariffs (flat and time of use) for low, medium, and high consumption households. However, its cost-effectiveness for a very high consumption household depends on the maximum peak load of the household during the demand charge period.

The results have demonstrated that the energy cost can be reduced using an appropriate battery energy management strategy (*EMS*); however, one strategy does not necessarily work well for all types of tariff structures. It was observed that the *EMS* with discharging constraint during the summer peak period is the most economical one for one *ToUD* ($ToUD_1$); however, it is not beneficial for the other *ToUD* ($ToUD_2$). With the optimally sized battery and suitable *EMS*, the annual energy cost is found to be the lowest for $ToUD_1$ among all tariffs and is reduced by 13% compared to the 'PV only' case. Moreover, $ToUD_1$ has the potential to reduce grid peak load demand. The results show that $ToUD_1$ can reduce peak load demand by 35.6%, 12.4%, and 12.4% compared to ToU_1, flat, and $ToUD_2$ tariffs, respectively. Therefore, *ToUD* presents an excellent opportunity to reduce the pressure on the grid while reducing household energy cost, even though by a small margin. To make *ToU* tariffs more attractive to household customers, there is an opportunity for utilities to explore more cost-reflective time of use tariffs, for example, based on the real-time wholesale market price of electricity. The insights gained from this study will help in the creation of grid-friendly time of use tariffs.

IX. FUTURE WORK

Further investigations on the impact of real-time wholesale electricity prices on the energy economy of households with PV and optimally sized storage will be a worthwhile future direction to consider. Recent introduction of time of use tariffs having very low off-peak electricity prices is likely to entice customers to charge home batteries from the grid. It will be interesting to analyse the impact of such tariffs on household energy cost when batteries are charged from the grid instead of PV.

APPENDIX

The battery charging and discharging equations used in this study are represented by (A.1) and (A.2), as shown at the top of the page, respectively [13], [18]. Table 7 summaries the battery discharging periods for the various energy management strategies deployed for the time of use tariff (ToU_1).

Fig. 15 shows the battery discharge periods (indicated by double-headed arrows) for the time of use tariff (ToU_1).

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REFERENCES

[1] K. Herter and S. Wayland, "Residential response to critical-peak pricing of electricity: California evidence," *Energy*, vol. 35, no. 4, pp. 1561–1567, Apr. 2010, doi: 10.1016/j.energy.2009.07.022.
[2] (Dec. 2019). *Tariff Structure Statement Part B 2020–2025, SA Power Networks*. Accessed: Jan. 4, 2021. [Online]. Available: https://www.aer.gov.au/system/files/SAPN—Revised Proposal—Attachment 17—Tariff Structure Statement Part B—Explanatory Statement
[3] A. Higgins, G. Grozev, Z. Ren, S. Garner, G. Walden, and M. Taylor, "Modelling future uptake of distributed energy resources under alternative tariff structures," *Energy*, vol. 74, pp. 455–463, Sep. 2014, doi: 10.1016/j.energy.2014.07.010.
[4] A. Ghasempour and J. Lou, "Advanced metering infrastructure in smart grid: Requirements, challenges, architectures, technologies, and optimizations," in *Smart Grids: Emerging Technologies, Challenges and Future Directions*. New York, NY, USA: Nova, 2017.
[5] S. Young, A. Bruce, and I. MacGill, "Potential impacts of residential PV and battery storage on Australia's electricity networks under different tariffs," *Energy Policy*, vol. 128, pp. 616–627, May 2019, doi: 10.1016/j.enpol.2019.01.005.
[6] (2021). *Residential—Energy Price Fact Sheet for Time of Use Tariff With Demand Charge*. Accessed: Apr. 6, 2021. [Online]. Available: https://www.energymadeeasy.gov.au/plan?id=COV170792MRE1&postcode=5095
[7] M. Gitizadeh and H. Fakharzadegan, "Effects of electricity tariffs on optimal battery energy storage sizing in residential PV/storage systems," in *Proc. Int. Conf. Energy Efficient Technol. Sustainability*, Nagercoil, India, Apr. 2013, pp. 1072–1077, doi: 10.1109/ICEETS.2013.6533536.
[8] *Solar Energy in South Australia*. Accessed: Jan. 5, 2021. [Online]. Available: https://pv-map.apvi.org.au/historical
[9] *South Australia Set Stunning New Record, Solar Meets 106 PCT of Demand*. Accessed: Dec. 12, 2021. [Online]. Available: https://reneweconomy.com.au/solar-meets-all-of-south-australia-demand-and-more/
[10] *South Australian Load Profile*. AEMO. Accessed: Nov. 13, 2020. [Online]. Available: https://aemo.com.au/en/newsroom/media-release/solar-power-fuels-south-australias-total-energy-demand

[11] T. Brinsmead, P. Graham, J. Hayward, E. Ratnam, and L. Reedman. *CSIRO-Future Energy Storage Trends 2015*. Australian Energy Market Commission. Accessed: Jun. 24, 2020. [Online]. Available: https://doi.org/10.4225/08/5852dbcfaffc6

[12] Battery Price Reduction. Accessed: Jun. 13, 2020. [Online]. Available: https://about.bnef.com/blog/behind-scenes-take-lithium-ion-battery-prices/

[13] V. Sharma, M. H. Haque, and S. M. Aziz, "Optimal battery size for grid connected rooftop solar photovoltaic systems in South Australia," in *Proc. Australas. Universities Power Eng. Conf. (AUPEC)*, Melbourne, VIC, Australia, Nov. 2017, pp. 1–6, doi: 10.1109/AUPEC.2017.8282509.

[14] V. Sharma, M. H. Haque, and S. M. Aziz, "Annual electricity cost minimization for South Australian dwellings through optimal battery sizing," in *Proc. IEEE Milan PowerTech*, Milan, Italy, Jun. 2019, pp. 1–6, doi: 10.1109/PTC.2019.8810703.

[15] L. V. White and N. D. Sintov, "Health and financial impacts of demand-side response measures differ across sociodemographic groups," *Nature Energy*, vol. 5, no. 1, pp. 50–60, Dec. 2019, doi: 10.1038/s41560-019-0507-y.

[16] W. Anderson, V. White, and A. Finney, "Coping with low incomes and cold Homes," *Energy Policy*, vol. 49, pp. 40–52, Oct. 2012, doi: 10.1016/j.enpol.2012.01.002.

[17] S. Bouzarovski, S. Petrova, and R. Sarlamanov, "Energy poverty policies in the EU: A critical perspective," *Energy Policy*, vol. 49, pp. 76–82, Oct. 2012, doi: 10.1016/j.enpol.2012.01.033.

[18] V. Sharma, M. H. Haque, and S. M. Aziz, "Energy cost minimization for net zero energy Homes through optimal sizing of battery storage system," *Renew. Energy*, vol. 141, pp. 278–286, Oct. 2019, doi: 10.1016/j.renene.2019.03.144.

[19] J. Weniger, T. Tjaden, and V. Quaschning, "Sizing of residential PV battery systems," *Energy Proc.*, vol. 46, pp. 78–87, Jan. 2014, doi: 10.1016/j.egypro.2014.01.160.

[20] B. P. Numbi and S. J. Malinga, "Optimal energy cost and economic analysis of a residential grid-interactive solar PV system-case of eThekwini municipality in South Africa," *Appl. Energy*, vol. 186, pp. 28–45, Jan. 2017, doi: 10.1016/j.apenergy.2016.10.048.

[21] J. Li, "Optimal sizing of grid-connected photovoltaic battery systems for residential houses in Australia," *Renew. Energy*, vol. 136, pp. 1245–1254, Jun. 2019, doi: 10.1016/j.renene.2018.09.099.

[22] G. Carpinelli, S. Khormali, F. Mottola, and D. Proto, "Battery energy storage sizing when time of use pricing is applied," *Sci. World J.*, vol. 2014, pp. 1–8, Jan. 2014, doi: 10.1155/2014/906284.

[23] V. Sharma, M. H. Haque, and S. M. Aziz, "Comparative evaluation of alternative tariffs on energy cost of households with PV and battery," in *Proc. 29th Australas. Universities Power Eng. Conf. (AUPEC)*, Nadi, Fiji, Nov. 2019, pp. 1–6, doi: 10.1109/AUPEC48547.2019.211928.

[24] S. B. Sepúlveda-Mora and S. Hegedus, "Making the case for time-of-use electric rates to boost the value of battery storage in commercial buildings with grid connected PV systems," *Energy*, vol. 218, Mar. 2021, Art. no. 119447, doi: 10.1016/j.energy.2020.119447.

[25] M. Zeraatpisheh, R. Arababadi, and M. Saffari Pour, "Economic analysis for residential solar PV systems based on different demand charge tariffs," *Energies*, vol. 11, no. 12, p. 3271, Nov. 2018, doi: 10.3390/en11123271.

[26] W. Kong, F. Luo, Y. Jia, Z. Y. Dong, and J. Liu, "Benefits of home energy storage utilization: An Australian case study of demand charge practices in residential sector," *IEEE Trans. Smart Grid*, vol. 12, no. 4, pp. 3086–3096, Jul. 2021, doi: 10.1109/TSG.2021.3054126.

[27] N. R. Darghouth, G. Barbose, J. Zuboy, P. J. Gagnon, A. D. Mills, and L. Bird, "Demand charge savings from solar PV and energy storage," *Energy Policy*, vol. 146, Nov. 2020, Art. no. 111766, doi: 10.1016/j.enpol.2020.111766.

[28] L. Bloch, J. Holweger, C. Ballif, and N. Wyrsch, "Impact of advanced electricity tariff structures on the optimal design, operation and profitability of a grid-connected PV system with energy storage," *Energy Informat.*, vol. 2, no. S1, pp. 1–19, Sep. 2019, doi: 10.1186/s42162-019-0085-z.

[29] J. Jin and Y. Xu, "Optimal storage operation under demand charge," *IEEE Trans. Power Syst.*, vol. 32, no. 1, pp. 795–808, Jan. 2017, doi: 10.1109/TPWRS.2016.2553961.

[30] J. Yu, J. Qin, and R. Rajagopal, "On certainty equivalence of demand charge reduction using storage," in *Proc. ACC*, Seattle, WA, USA, May 2017, pp. 3430–3437, doi: 10.23919/ACC.2017.7963477.

[31] F. Luo, W. Kong, G. Ranzi, and Z. Y. Dong, "Optimal home energy management system with demand charge tariff and appliance operational dependencies," *IEEE Trans. Smart Grid*, vol. 11, no. 1, pp. 4–14, Jan. 2020, doi: 10.1109/TSG.2019.2915679.

[32] J. B. Abikarram, K. McConky, and R. Proano, "Energy cost minimization for unrelated parallel machine scheduling under real time and demand charge pricing," *J. Cleaner Prod.*, vol. 208, pp. 232–242, Jan. 2019, doi: 10.1016/j.jclepro.2018.10.048.

[33] A. Ghasempour and M. B. Menhaj, "A new genetic based algorithm for channel assignment problems," in *Computational Intelligence, Theory and Applications*, B. Reusch, Ed. Berlin, Germany: Springer, 2006, pp. 85–92.

[34] V. Sharma, S. M. Aziz, M. H. Haque, and T. Kauschke, "Effects of high solar photovoltaic penetration on distribution feeders and the economic impact," *Renew. Sustain. Energy Rev.*, vol. 131, Oct. 2020, Art. no. 110021, doi: 10.1016/j.rser.2020.110021.

[35] *Australian/New Zealand Standard: Grid Connection of Energy Systems Via Inverters*, AS 4777.2:2015, Standards Australia, NSW, Australia, 2015.

[36] *Time of Use Pricing in Australia*. Accessed: Feb. 5, 2020. [Online]. Available: https://www.solarchoice.net.au/blog/time-of-use-tariff-schedules

[37] S. Zhang and Y. Tang, "Optimal schedule of grid-connected residential PV generation systems with battery storages under time-of-use and step tariffs," *J. Energy Storage*, vol. 23, pp. 175–182, Jun. 2019, doi: 10.1016/j.est.2019.01.030.

[38] *Revised Tariff Structure Statement 2017-20—Part A*, SA Power Netw., SA, Australia, 2017.

[39] *Solar Feed-In-Tariff of South Australia*. Accessed: Dec. 12, 2020. [Online]. Available: https://www.sa.gov.au/topics/energy-and-environment/energy-bills/solar-feed-in-payments

[40] (2016). *Retailer Feed-In-Tariff-Review of Regulatory Arrangements*. Accessed: Nov. 29, 2020. [Online]. Available: https://www.escosa.sa.gov.au/ArticleDocuments/998/20161220-Electricity-RetailerFiT_ReviewRegulatoryArrangements-FinalDecision.pdf.aspx?Embed=Y

[41] T. Moore, "Strategic niche management and the challenge of successful outcomes," in *Urban Sustainability Transitions*. Singapore: Springer, 2017, pp. 109–126.

[42] (2018). *Solar Report, Australian Energy Council*. Accessed: Aug. 15, 2020. [Online]. Available: https://www.energycouncil.com.au/media/14635/aec-solar-report_-q3-2018_final.pdf

[43] *Retail Electricity Prices for 2017/2018 by State*. Accessed: Feb. 5, 2020. [Online]. Available: https://theconversation.com/factcheck-qanda-are-south-australias-high-electricity-prices-the-consequence-of-renewable-energy-policy-93594

[44] *Red Flow Battery*. Accessed: Feb. 5, 2020. [Online]. Available: https://redflow.com/products/zcell/

[45] *Sonnen Battery*. Accessed: Jan. 1, 2020. [Online]. Available: https://www.zenenergy.com.au/solar-battery-storage/zen-sonnen/

[46] *Tesla Powerwall Battery Warranty and Price*. Accessed: Dec. 6, 2019. [Online]. Available: https://www.solarchoice.net.au/blog/tesla-powerwall-2-australia

[47] (2019). *Energy Consumption of Households*. Accessed: Sep. 24, 2019. [Online]. Available: https://www.energymadeeasy.gov.au/plan?id=DIA81378SRE1&post code=5095

[48] V. Sharma, M. H. Haque, and S. M. Aziz, "PV generation and load profile data of net zero energy Homes in South Australia," *Data Brief*, vol. 25, Aug. 2019, Art. no. 104235, sdoi: 10.1016/j.dib.2019.104235.

[49] *Renewable Ninja Web Platform*. Accessed: Jun. 24, 2020. [Online]. Available: https://www.renewables.ninja/

[50] (2020). *Residential-Energy Price Lightning Plan for Time of Use Tariff*. Accessed: Apr. 5, 2020. [Online]. Available: https://www.ioenergy.com.au/OurPlans/

[51] (2020). *Residential-Energy Price Fact Sheet*. Accessed: Apr. 6, 2020. [Online]. Available: https://diamondenergy.com.au/epfs/resi/market/sapn.pdf

[52] *AGL Retail Electricity Prices*. Accessed: May 11, 2020. [Online]. Available: https://www.agl.com.au/help/rates-contracts/standard-contracts?cidi=A10038

[53] Y. Wang, R. Das, G. Putrus, and R. Kotter, "Economic evaluation of photovoltaic and energy storage technologies for future domestic energy systems—A case study of the U.K.," *Energy*, vol. 203, Jul. 2020, Art. no. 117826, doi: 10.1016/j.energy.2020.117826.

[54] (2018). *Home Battery Scheme South Australia*. Accessed: May 5, 2020. [Online]. Available: https://homebatteryscheme.sa.gov.au/

[55] I. Alsaidan, A. Khodaei, and W. Gao, "A comprehensive battery energy storage optimal sizing model for microgrid applications," *IEEE Trans. Power Syst.*, vol. 33, no. 4, pp. 3968–3980, Jul. 2018, doi: 10.1109/TPWRS.2017.2769639.

[56] *Tesla Powerwall Datasheet*. Accessed: Dec. 6, 2019. [Online]. Available: https://www.tesla.com/sites/default/files/pdfs/powerwall/Powerwall%202_AC_Datasheet_en_AU.pdf

[57] *Evolve Home Energy Storage Datasheet*. Accessed: Feb. 6, 2022. [Online]. Available: https://www.eguanatech.com/_resources/Installer_Resources/Evolve%200513U/58148%20Evolve%200513U%20Datasheet.pdf

[58] *LG Resu 10 Datasheet*. Accessed: Feb. 16, 2022. [Online]. Available: https://www.acsolarwarehouse.com/wp-content/uploads/2017/09/RESU10H_R_Data-sheet_ver1.0_170221.pdf

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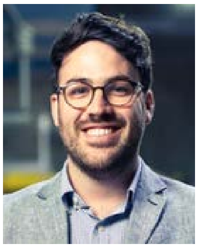

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