A Price Regulated Electric Vehicle Charge-Discharge Strategy for G2V, V2H and V2G

Ujjwal Datta*, Nithya Saiprasad, Akhtar Kalam, Juan Shi and Aladin Zayegh

College of Engineering and Science, Victoria University, Melbourne, Australia

SUMMARY

Electric Vehicles (EVs) and smart grids are gradually revolutionizing the transportation sector and electricity sector respectively. In contrast to unplanned charging/discharging, smart use of EV in Home Energy Management System (HEMS) can ensure economic benefit to the EV owner. Therefore, this paper has proposed a new energy pricing controlled EV charging/discharging strategy in HEMS to acquire maximum financial benefit. EV is scheduled to be charged/discharged according to the price of electricity during peak and off-peak hours. In addition, two different types of EV operation modes i.e. Grid-to-Vehicle (G2V) in off-peak time and Vehicle-to-Home (V2H) in on-peak time are considered to determine comparative economic benefit of planned EV charging/discharging. The real load profile of a house in Melbourne and associated electricity pricing is selected for the case study to determine the economic gain. The simulation results illustrate that EV participating in V2H contributes approximately 11.6% reduction in monthly electricity costs compared to G2V operation mode. Although the facility of selling EV energy to the grid is not available currently, the pricing controlled EV charging/discharging presented in the paper can be used if such facility becomes available in the future.

KEY WORDS

Electric vehicle, charging/discharging strategy, economic benefit, vehicle-to-home (V2H), grid-to-vehicle (G2V)

Correspondence

* Ujjwal Datta, College of Engineering and Science, Victoria University, Melbourne, Australia
Email: Ujjwal.datta@live.vu.edu.au

1. INTRODUCTION

Renewable Energy (RE) is gradually replacing fossil fuels in the electricity grids[1]. With the electric grid gradually evolving, the modern day power system integrating smart technologies have reached smart buildings and smart cities[2, 3]. Smart grids assisted with Automated Metering Infrastructure (AMI) communications and software platforms are attracting residential consumers to adopt Home Energy Management System (HEMS)[4]. EVs, another sustainable initiative in transportation industry, are proving to be a promising technology to mitigate GHG emission[5]. An increase of 54% in oil consumption by transport sector alone is expected by 2035 globally[6]. In another study, it is envisaged that internal combustion engine vehicles could eventually be substituted by EVs[7]. EV utilizes the battery storage technology that can be timely recharged through the electricity grid. EV charging in on-peak time may impose additional stress on peak electricity demand which could result in potential congestions on the power systems[8]. Off-peak EV charging would provide utilizing grid power at a cheaper price and also reduce peak time burden on the grid. On the contrary, discharging limit of EV is an important parameter to select, as it could disrupt EV availability for transportation purposes. Thus, a careful consideration has to be given in EV discharging for the efficient utilization of EV. As such, a well-defined strategy must be adopted for EV in HEMS application to contribute in V2H or G2V, making it a reliable option for both transportation and HEMS.

Several studies have been conducted on utilising EV as an energy backup in place of load shedding and community energy storage system to share the amount of energy between them. The study in[9, 10] demonstrated the dependence on energy storage system (ESS) to achieve financial gain for customers. EV for V2H facility as backup energy supply to mitigate load shedding has been studied in[11]. On the other hand, EV as a power backup for longer hours has been proposed in[12]. The study in[13] demonstrated that EV energy sharing between the houses in a community through centralised and dispersed charging facility can competently improve the reliability of the supply in a distribution system. Further, the distribution system can be benefited from dispersed charging as EV industry evolves with higher energy and power capacities. A simulation study of HEMS and efficient utilization of EV plug-in technology for a household electricity demand has been conducted in[14]. Considering PVs as an alternate energy source to meet the requirement of the load, the study[14] has highlighted minimising electricity cost by optimally scheduling electrical appliances of a house along with V2H technology. The impact of integrated EV as V2H is proposed in[15] to design optimal size of renewable energy sources for smart home environment. Shifting the energy consumption profile according to the electricity price is proposed in[16] to reduce energy bills and lowering transformer loading. EV is utilized in reducing peak load demand throughout peak pricing period to minimise electricity purchasing costs of consumers[17-20]. EV as V2H is studied in[21] to reduce peak time load demand and interruption costs during power outage. EV battery is discharged to the minimum state-of-charge (SOC), EV is placed at home throughout the day i.e. constant SOC in day time to provide similar cost saving purpose. EV is also used to reduce peak load demand and selling excess energy to the grid, but then again EV is exploited throughout the day that reflects EV predominantly being used as storage device rather than a vehicle.

Few analysis of EV cost benefit has been in earlier studies. The study in[22] demonstrated the potential benefit of EV in vehicle-to-grid (V2G). Another study in[23] has shown that disordered charging of EV is costlier than intelligent charging for the EV owner. An EV charging and discharging strategy is proposed in[24] to minimise the electricity cost of residential customer using G2V, V2G and V2H modes of operation. The financial impact on the residential customer using single and dual EV has been analysed. However, the study focus is limited to on-peak and off-peak hours only. The main tenacity of EV i.e. driving should be given highest priority above any charging/discharging strategy. Discharging strategy considering EV presence at home throughout the day time or discharging to a minimum SOC level is not a realistic approach because this may interrupt the flexibility of driving to meet consumer needs. The studies in[25,26] have demonstrated the benefit of controlled charging in terms of lower charging costs, reduced peak demand and network losses. However, EV for V2H or V2G is not considered in the study.

In this paper, a dynamic energy pricing regulated EV charging/discharging control strategy is proposed. The main advantage of the proposed strategy is that, this can be utilised for different electricity markets i.e. dynamic pricing and/or on/off-peak pricing based energy market in V2G or V2H mode. The calculation of power and energy pricing are presented for three different EV operation modes, namely V2H, G2V and V2G. The objective of the proposed research is to minimise daily/monthly electricity costs of EV owner by effectively managing EV charging/discharging and curtailing grid consumptions during peak pricing period. The control strategy is adopted assuming that the customer is a traditional full time employee having a fixed departure and arrival time. Currently, there is no provision of selling electricity to the grid from EV or other storage systems during peak time to the grid in Melbourne, Victoria, Australia hence, EV as V2G is not considered for economic analysis in this study. The main objective is to carry out a comparative economic analysis between EV in G2V only and V2H with G2V and investigate EV contribution in total electricity costs for the EV owner. In addition, if energy selling price is available in the future, the proposed method can be easily utilized to calculate comparative economic benefit for all three EV operating modes.

Section 2 discusses the EV potential and smart use of EV in Australian household. EV operation modes, EV power and SOC calculation are outlined in section 3. The detailed discussion of the proposed methodology is presented in section 4. Section 5 illustrates the description of the studied system. Results and discussions are presented in section 6. Section 7 discusses the main conclusion of the study.

2. EV POTENTIAL AND HEMS IN AUSTRALIAN HOUSEHOLD

2.1 Typical Household Energy Consumption in Australia

Typical energy consumption in a residential house depends on several factors such as number of occupants, house type and size, energy mix, energy efficiency of the appliances, available electricity pricing policy and life style of the occupants. The average residential energy consumption profile based on a study by the Australian Energy Regulator (AER) in 2017[27] on 8,174 households illustrates that consumption level varies across different regions in Australia. The annual energy consumptions by the most common household types without swimming pool are shown in Fig. 1 based on AER survey. The daily energy consumption in New South Wales (NSW) are approximately 23.5 kWh, 17.8 kWh in Queensland Zone 1, 8.4 kWh in SA Adelaide whereas in Victoria (VIC) Zone 6, it is 12.5 kWh. The maximum daily consumption is 24.2 kWh in Northern Territory.

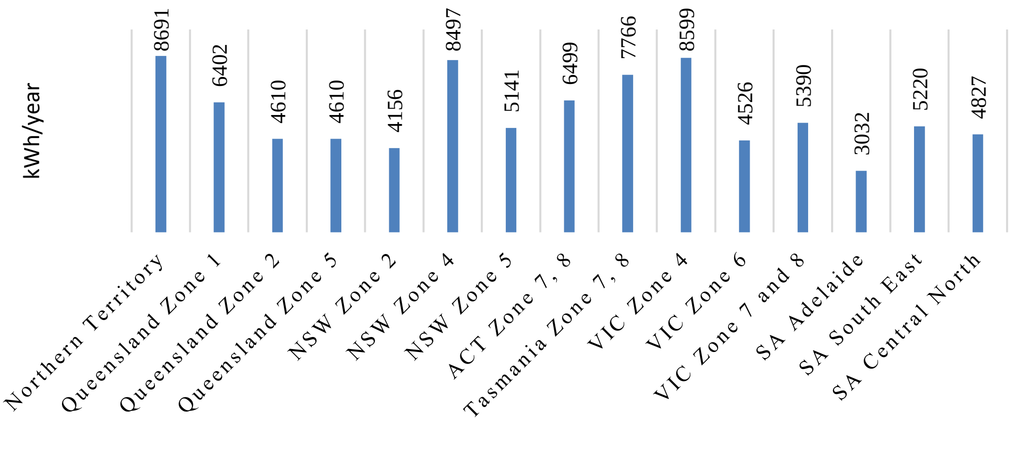

Figure 1 The annual residential energy consumption profile with 2 person in Australia, 2017

2.2 Market Potential of EV in Australia

In a recent article[28], EV potential in Australian transportation industry is investigated and it is highlighted that based on existing poor public transport system, less population in large geographical area and high costs, EV has enormous prospect in Australia. There has been significant growth in car ownership between 2011 and 2016 in Australia with 84.4% of the households owned at least one car and 61.1% having two or more cars[29]. At present, there are approximately 7340 EVs in Australia[30]. However, EV sales are estimated to increase steadily by about 27.1% per annum between 2016 and 2036[31]. The growth in EV sales increased to

67% in 2017[30] compared to 2016 and this represents 0.2% of the total Australian car market. In addition, there is a 64% increase in the number of charging station location which clearly indicates that Australian transportation industry is preparing for EV uptake in the coming future.

2.3 Smart use of EV in Australian House

In Australia, it is projected that number of households will increase nearly 12.7 million by 2036 with a population growth of 32.4 million i.e. 45% growth in population compared to 2011[32]. With the growing population, numbers of vehicles are also expected to increase. In consideration of regulation change of EV import, incentives for EV purchase, availability of EV models, it is forecasted that number of EVs on the road will reach more than 17.7% of total vehicles by 2036. Managing such a huge infiltration of EVs is demanding and requires effective planning. Australia's first EV trial in Western Australia in 2012 demonstrates that peak charging time is 8-10 am in business and station area[33]. The study also suggested that PV generation can offset charging demand using solar energy. However, as the actual price for charging from PV is not different than conventional energy price, EV owner is not getting any financial benefit from such charging strategy. Another trial in Queensland by Ergon energy found that EV charging impact is visible between 6-8 pm[34]. Such recharging strategy in peak time not only impacts heavily on the grid but also increases the costs for EV recharging. Therefore, considering the estimation of EV uptake in the future, longer on-peak time with higher price, EV has great potential for participating in grid or home energy management. However, an economic charging/discharging strategy is essential to provide technical and economic advantage to the EV owner. Hence, in this study, EV discharging for reducing on-peak energy consumption and recharging in off-peak time is proposed, from the perspective of EV potential in Australia.

3. EV DEVELOPMENT AND EV POWER CALCULATION

3.1 V2H, V2G and G2V Development with EV

EV when connected to house via a bi-directional AC/DC converter can be used in V2H or V2G mode of operation to increase the reliability of house or the network electricity supply. The three EV operating modes, G2V, V2G and V2H can reduce operating costs for a house owner, given that proper charging/discharging strategy with energy pricing is adopted. However, the level of EV participation in different EV operating modes always depends on customer's preference and SOC availability.

3.2 EV Power and SOC Calculation

The power balance equation in a house with EV, including EV charging/discharging at any other period must satisfy the condition as in equation (1),

$$P_{total}(t) = P_{demand}(t) + S(t) * P_{EV}(t) \tag{1}$$

where,

P_{total} = Total grid power

P_{demand} = House load power demand

S = Status of EV {plugged-in (S=1), unplugged (S=0)} at time t (hour)

P_{EV} = EV power output during charging (+ve)/discharging (-ve) period.

In this paper, we assumed that 7am in the morning is when the typical EV is plugged out and plugged-in time is 5pm. The typical calculation of EV battery SOC is based on the coulomb counting method in equation (2),

$$SOC_t = SOC_{(t-1)} + \frac{1}{C_{batt}} \int_0^t I_t \, dt \tag{2}$$

where,

I_t = EV battery charge/discharge current

SOC_t = initial SOC at t = 0

C_{batt} = EV battery capacity in ampere-hour

Battery charger and battery efficiency play an important role when participating in V2H or V2G. As there are certain amount of losses while converting power, hence the total EV capacity is not available during discharging of EV in HEMS. Therefore, an approximate 90% efficiency is considered for EV battery charger and EV battery itself during EV as V2H/V2G that implies lower available EV battery capacity during V2H/V2G.

4 CHARGING/DISCHARGING STRATEGY AND ENERGY PRICING

The adopted control strategy regulates EV charging/discharging according to the electricity price set by the grid. Therefore, this control approach can be exploited in any energy market depending on various pricing schemes in a smart grid environment.

4.1 Charging/Discharging Strategy for G2V, V2G and V2H

This section illustrates EV charging/discharging strategy adopted in smart HEMS. The best practice to reduce electricity costs is to charge battery during low pricing off-peak period and discharge it during high pricing peak periods. EV for V2G, G2V and V2H is primarily controlled by EV status and secondarily regulated by energy price, available battery SOC and EV power injection for V2G/V2H. EV participation according to electricity costs (EC) in G2V only is expressed in equation (3)

$$P_{EV}(t) = \begin{cases} P_{EV/ch-G2V}(t), & if\ EC_{off-peak} \le EC_{on-peak},\ \text{or}\ t = time_{off-peak} \\ & and\ SOC(t) \le SOC_{max} \\ 0, & otherwise \end{cases} \tag{3}$$

where,

$P_{EV/ch-G2V}(t)$ = EV power in charge mode

$EC_{on-peak}$ = Electricity costs/kWh (on-peak)

$EC_{off-peak}$ = Electricity costs/kWh (off-peak)

In V2H application, total EV power calculation can be expressed in equation (4)

$$P_{EV}(t)=\begin{cases} P_{V2H/disch}(t), & if\ EC_{on-peak} > EC_{off-peak},\ \text{or}\ t = time_{peak}\ and\ SOC(t) \geq SOC_{min-threshold} \\ P_{EV/ch-G2V}(t), & if\ EC_{off-peak} \leq EC_{on-peak},\ \text{or}\ t = time_{off-peak}\ and\ SOC(t) \leq SOC_{max} \\ 0, & otherwise \end{cases} \tag{4}$$

where,

$SOC_{min-threshold}$ = Minimum SOC preferred by the owner

$P_{V2H/disch}(t)$ = Discharge EV power in V2H mode

In V2G mode, EV should meet the entire house load demand before it participates in V2G considering single connection point of power export and import and that can be defined as in equation (5)

$$P_{EV}(t) = P_{EV/disch}(t) > P_{demand}(t) \tag{5}$$

Thus, in V2G operation mode, total EV power calculation with V2G and G2V is written as in equation (6)

$$P_{EV}(t)=\begin{cases} P_{V2G/disch}(t), & if\ EC_{peak-sell} > EC_{on-peak},\ \text{or}\ t = time_{peak}\ and\ SOC(t) \geq SOC_{min-threshold} \\ P_{EV/ch-G2V}(t), & if\ EC_{off-peak} \leq EC_{on-peak},\ \text{or}\ t = time_{off-peak}\ and\ SOC(t) \leq SOC_{max} \\ 0, & otherwise \end{cases} \tag{6}$$

where,

$P_{V2G/disch}(t)$ = Discharge EV power in V2G mode

Thus, the total power at grid connection point will be negative as shown in equation (7) that resembles power export to the grid.

$$P_{total}(t) = P_{demand}(t) - S(t) * P_{V2G/disch}(t) \tag{7}$$

The controller must ensure that battery $SOC(t)$ stays within customer preferred level to ensure driving resolution is always conceivable,

$$SOC_{min-threshold} < SOC_t < SOC_{max} \tag{8}$$

4.2 Energy Pricing for G2V, V2H and V2G

The key purpose is to use EV in different operating modes and analyse comparative economic benefits in minimising the electricity costs by adopting numerous charging/discharging strategies considering off-peak and peak pricing. It is worthwhile to mention, economic benefit is significantly delineated by electricity pricing for each EV operation mode. The typical electricity pricing calculation without any EV for the house owner is shown in equation (9)

$$\sum_{0}^{t} CE_T(t) = \sum_{off-peak_{min}(t)}^{off-peak_{max}(t)} P_{demand}(t) * EC_{off-peak}(t) + \sum_{peak_{min}(t)}^{peak_{max}(t)} P_{demand}(t) * EC_{on-peak}(t) \tag{9}$$

$CE_T(t)$ = Total costs of electricity

In G2V, i.e. EV charging only in off-peak period, total electricity costs are calculated as follows,

$$\begin{aligned}\sum_{0}^{t} CE_T(t) = &\sum_{off-peak_{min}(t)}^{off-peak_{max}(t)} \{P_{demand}(t) + S(t) * P_{EV/charge-G2V}(t)\} * EC_{off-peak} + \\ &\sum_{peak_{min}(t)}^{peak_{max}(t)} P_{demand}(t) * EC_{on-peak}(t)\end{aligned} \tag{10}$$

EV charging power cost reflects the additional costs incurred by the house owner. The overall electricity price will be less when EV is charged at low pricing periods compared to charging at peak periods. Therefore, adopting proper EV charging is one of the smartest moves to be implemented in HEMS to reduce customer's electricity costs. The electricity costs calculation in V2H in peak time and G2V in off-peak are expressed as in equation (11)

$$\begin{aligned}\sum_{0}^{t} CE_T(t) = &\sum_{off-peak_{min}(t)}^{off-peak_{max}(t)} \{P_{demand}(t) + S(t) * P_{EV/charge-G2V}(t)\} * EC_{off-peak} \\ &+ \sum_{peak_{min}(t)}^{peak_{max}(t)} \{P_{demand}(t) - S(t) * P_{V2H/discharge}(t)\} * EC_{on-peak}(t)\end{aligned} \tag{11}$$

The economic benefit in V2G mode largely depends on electricity selling price and associated costs for any communication or contractual setup for V2G participation. The energy pricing with G2V in off peak and V2G in peak time are calculated as in equation (12)

$$\begin{aligned}\sum_{0}^{t} CE_T(t) = &\sum_{off-peak_{min}(t)}^{off-peak_{max}(t)} \{P_{demand}(t) + S(t) * P_{EV/charge-G2V}(t)\} * EC_{off-peak} + \\ &\sum_{peak_{min}(t)}^{peak_{max}(t)} \{P_{demand}(t) - S(t) * P_{V2G/discharge}(t)\} * EC_{peak-sell}(t)\end{aligned} \tag{12}$$

where,

$EC_{peak-sell}(t)$ = Energy selling price in V2G period

The SOC in V2G drains more quickly than V2H. At a point when V2G or V2H operation mode is not possible to continue due to insufficient EV SOC, the basic energy pricing will substitute the pricing in V2G or V2H. The power and associated energy calculations conducted in this paper is shown in Figure 1.

In the first step, the algorithm checks the status of EV. If EV is not available, the power and energy are calculated based on typical house load power demand using equations (1) and

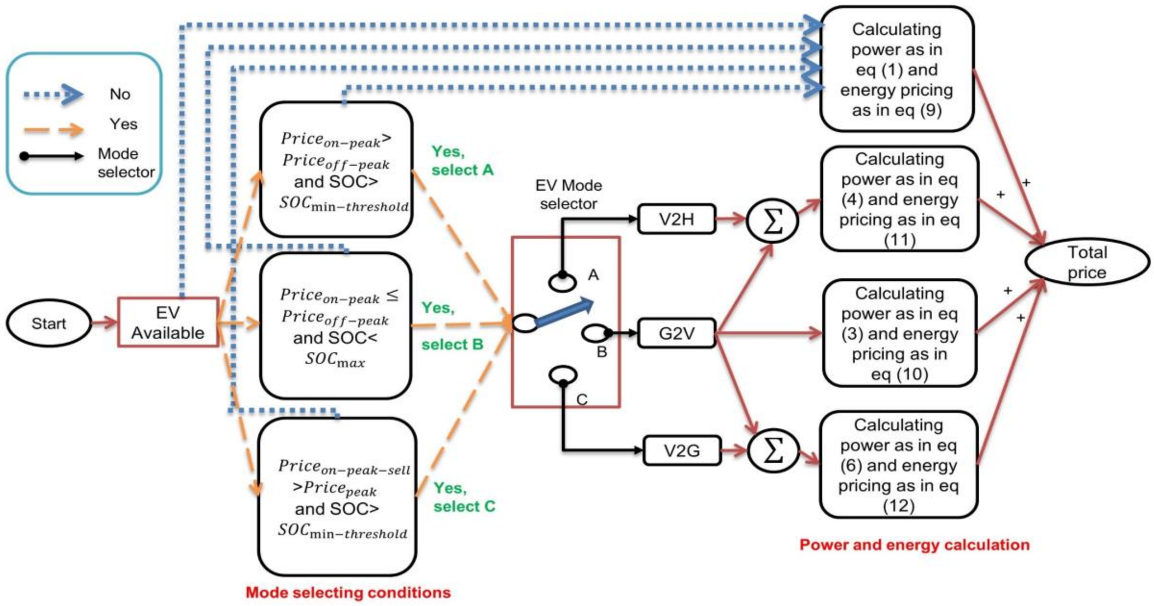

Figure 1 The selection of EV operation modes, power and associated energy calculation

(9). When EV is available, it examines the on/off-peak energy pricing and SOC status of EV. EV mode selector receives this signal and selects the appropriate EV operation mode according to the fulfilment of mode selecting conditions. Once the EV operation mode is chosen, associated power and energy are calculated following the respected equations mentioned in Sections 4.1 and 4.2.

5. SYSTEM DESCRIPTION

A typical schematic diagram of EV for grid connected smart HEMS arrangement is shown in Figure 2. The system consists of EV battery and house load demand profile. The total rated EV battery capacity is 23kWh. When participating in V2G/V2H, the available EV capacity becomes 20.7kWh with 90% efficiency. Considering EV operation modes, power exchanges are split into two types, namely power transaction from the grid known as energy buying (G2V) and power transaction within the house (V2H).

Depending on hourly varying energy prices and EV availability, EV owner may decide for any arrangement of V2H, V2G and G2V. To calculate monthly energy billing, a net metering approach is adopted. The energy selling and buying prices are not the same. Currently, feed-in tariff in Australia is only available for renewable energy sources such as solar or wind. Hence, as there are no schemes presently for customers to selling energy during on-peak time from storage devices such as battery or EV, economic comparison of V2H and V2G is not possible to carry out. As a result, in this paper comparative economic analysis will be limited to V2H and G2V only. Nevertheless, EV for V2G operation and relevant calculation techniques of energy pricing are presented, hence, this can be easily calculated if future energy market has the feature of selling energy to the grid. A simple charging/discharging strategy is proposed to determine economic benefit of EV participation in home energy management as V2H and G2V. The most important advantage of the proposed strategy is that this avoids any complexity related to participation in community or grid control power exchange. This will make it easy to determine the operation mode that is economical by reducing significant portion of total electricity expenses over other modes and maximise welfare profit. In Australia, daily on-peak and off-peak energy pricing schemes differs by a large margin i.e. nearly 50% higher price during on-peak than off-peak hours that give rise to

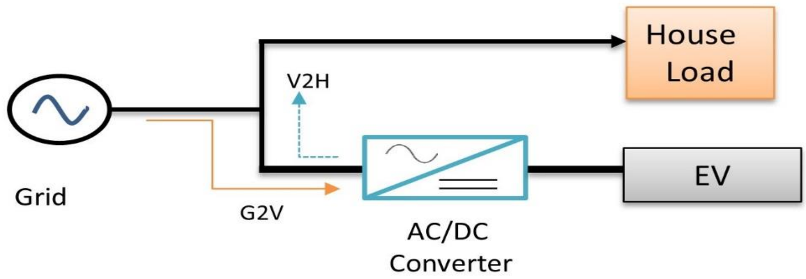

Figure 2 The system architecture of HEMS with EV

the importance of EV participation in HEMS. Moreover, the uncertainty of EV presence plays significant role in EV operation mode, however long duration of on-peak pricing encourages EV to take part in HEMS, during peak hours. In term of end-user demand nature, historical behaviour of the customer is a significant parameter to decide and design cost-effective EV usage during peak demand/peak pricing periods.

Currently, bi-directional EV battery charger is not commercially available as built-in facility in most of the available EVs. For existing customers, bi-directional EV charger can be purchased separately but this will incur additional costs. However, with the advancements in power electronics, such facility will be built-in in the future with the new EVs such as Nissan Leaf[35]. Moreover, considering EV penetration ratio in the future power system, potential EV market, rooftop PV, possible economic benefit of EV as V2G and V2H, the costs of bi-directional EV charger will be very insignificant and may be available with every EV to attract more customers to purchase EV. Therefore, there may not be need for additional costs for EV to participate in V2H/V2G in the coming future.

6. RESULT AND DISCUSSION

The costs of electricity in the case of no EV and EV with V2H, G2V are calculated and the comparative benefit is highlighted in this Section. The power exchange during V2H and G2V, EV battery SOC during charging/discharging and associated energy pricing is added to the daily electricity consumptions in order to calculate the total energy pricing for a day. Furthermore, the total electricity costs for a month is also calculated using weekdays and weekend pricing according to Victorian residential energy pricing[36].

6.1 Comparative economic benefit of smart EV usage in a day

The real load profile of a Victorian house in Melbourne, Australia is considered for V2H and G2V for peak time consumptions in a day. In Melbourne, the duration of peak energy pricing period is 7am-11pm as shown in Table 1. During day time in weekdays, EV is not available therefore EV cannot be used for V2H. The energy pricing is based on actual pricing by the energy supplying utility including goods and services tax (GST)[36].

Table 1 *Dynamic electricity pricing in Victoria, Melbourne, Australia*

Residential 5-day Time of Use	Price/kWh (A$) (Inc. GST)
On-peak (weekdays, 7am-11pm)	0.341
Off-peak usage (all other time including whole weekends)	0.16973

The energy calculation for one day (4th June 2018) in different EV scenarios is highlighted for a residential household in Victoria. If the electricity price is the same for on-peak and off-peak periods, EV will not participate in V2H and therefore EV will only be charged in G2V mode. The results are carried out considering on-peak electricity price is higher than the off-peak price. Figure 3 shows the aggregated energy for every 30 minutes that demonstrates higher energy consumption during off-peak periods (starting from 11pm to 7am in the next morning) for V2H compared to G2V. Figure 4 highlights the status of EV SOC during 24-hours for different EV operation modes. At 11pm, EV kicks off charging and therefore EV SOC starts to increase. The status of energy and SOC calculation is updated at every 30 minutes interval and hence the updated value of energy (increased) and SOC (increased) can be visible at 11:30pm as presented in Figures 3 and 4. For both EV operation modes, SOC reaches to maximum level before the next morning. Three different scenarios of with no EV and EV operation modes are explained as follows:

Scenario 1 (No EV): It can be clearly understood from Figure 3 that the energy consumption of the house is on-peak in the evening after 6pm till 11pm. The total electricity cost for the day, without an EV, is A$6.1459 as shown in Table 2. Between 6-11pm, the electrical load power demand of the house is more than 1kW. It should be noted that, the on-peak hours of electrical pricing in Victoria is until 11pm on a weekday.

Scenario 2 (EV charged by the grid - G2V only): In the presence of EV, if the grid charges the EV (G2V), this will impose additional load to the pre-existing electrical load of the house. EV should be fully charged by the next morning so that EV is ready for driving. Charging of EV will impose higher power consumption which will be reflected in total electricity costs of the house. If EV is charged during the evening peak time, electricity costs will be very high compared to off-peak charging. Therefore, controlled off-peak charging is proposed in this study to maximise economic gain of EV usage. Considering off-peak energy price between 11pm to 7am, if the EV is charged during the period, the total price of the electricity consumption including typical house load demand is A$9.1604.

Scenario 3 (EV discharged to house and charged by the grid, V2H + G2V): EV battery is charged by consuming energy from the grid and utilizing this energy for transportation purposes during the day. Assuming that SOC of the battery is 0.6pu when EV is at home and hence, EV battery energy is available to meet household demand by the evening (after 6pm when the electrical load of the house is high and grid energy price is in its peak during this interval). It can be observed from Figure 4 that EV SOC reduces to 0.39pu in the case of V2H + G2V and therefore consumes more energy during charging time than EV as G2V only. In G2V only, EV SOC does not change significantly except minor self-discharge of the battery.

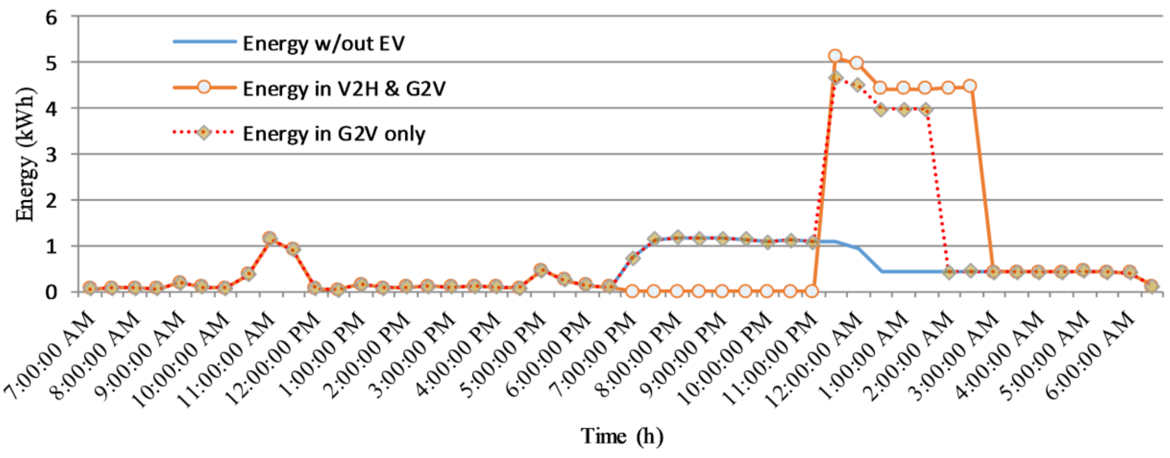

Figure 3 The energy per 30 minutes for one day in different EV operation modes

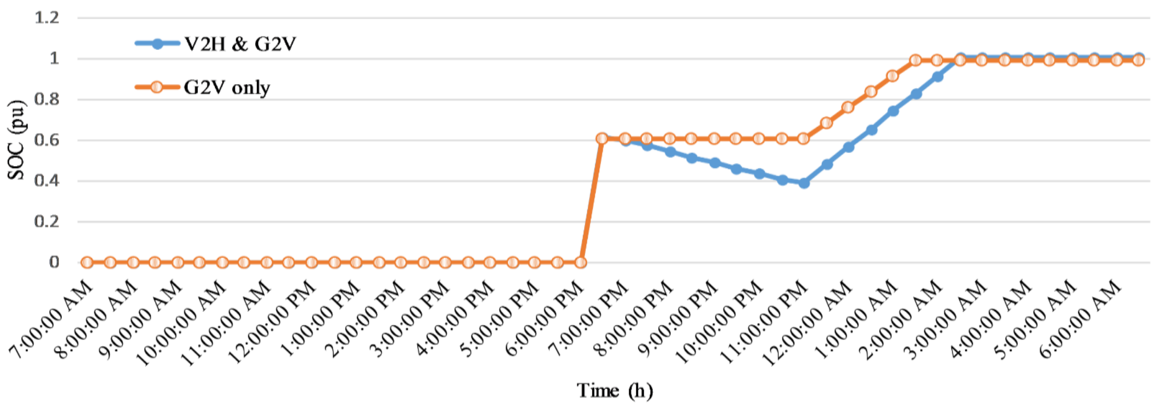

Figure 4 EV battery SOC for V2H + G2V and G2V only

The comparative economic analysis is highlighted in Table 2. The results suggest that, there is an additional cost of A$3.0145 in a day on off-peak controlled charging EV from the grid (G2V) compare to no EV. However, when EV is used for V2H during on-peak pricing period, the total electricity costs of the house is reduced to A$7.5899. This implies that, there is an approximately savings of A$1.5705 on supplying energy to the house by EV discharging. From the calculations as encapsulated in Table 2, it can be noted that, if EV is intelligently utilized to meet peak load demand, significant economic advantage is possible to be incurred by the EV owner. As shown in Figure 3, EV is fully charged by 1:30am for G2V only and at 2:30am for V2H + G2V. Therefore, EV can be easily charged at reduced power from the grid with long charging periods for V2H + G2V.

TABLE 2 *Comparative daily economic benefit with various EV operation modes*

EV operation modes	Price comparison (AUD)
Pricing without EV	6.1459
Pricing With EV, W/out Peak load reduction (G2V)	9.1604
Pricing With EV, With Peak load reduction (V2H+G2V)	7.5899
Additional costs of EV charging	3.0145
V2H benefit over G2V only	1.5705

6.2 Comparative economic benefit of smart EV usage in a month

The comparative economic study is extended for a month to determine the overall EV contribution in reducing electricity costs. While off-peak and on-peak pricing are available during weekdays, weekend is priced at off-peak rate only as outlined in Table 1. Therefore, it is not economical to discharge EV battery for V2H considering EV stays at home during the weekend. However, if EV is used during the weekends, the pricing will be different than what is presented in this paper. It is obvious that battery will have self-discharge and therefore EV battery SOC will be reduced. However, for simplicity it is assumed that EV battery SOC does not change significantly during the weekend with no EV operation.

The economic analysis results of a month are highlighted in Table 3. For Scenario 1, it should be noticed that the total energy costs purchased from the grid in a month is approximately A$107.288. This is the price for the energy purchased in the absence of EV.

On the contrary, the total electricity costs of the house raises by A$43.505 when EV is charged from the grid in G2V mode during off-peak time (controlled charging). The costs will be more if EV is charged during on-peak pricing periods with higher price/kWh. However, in V2H + G2V operating mode, the total monthly electricity costs for the house reduces by A$19.798 which manifests 11.6% reduction in monthly electricity bills. This advocates significant economic benefit of EV in HEMS to the EV owner, if charging/discharging is planned effectively.

TABLE 3 EV operation modes and Comparative economic benefit for one month

EV operation modes	Price comparison (AUD)
Pricing without EV	107.288
Pricing With EV, W/out Peak load reduction	170.591
Pricing With EV, With Peak load reduction	150.793
Additional cost of EV charging	43.505
V2H benefit over G2V only	19.798

Daily electricity costs for the month and the daily total energy consumptions are illustrated in Figures 5 and 6 for different cases, such as no EV and EV operating in different operation modes. Figure 5 demonstrates that EV in V2H reduces daily electricity costs compared to G2V. A small reduction in daily costs by V2H strongly claims an aggregated large economic benefit. During weekends, EV does not participate in V2H and considering insignificant changes in SOC, EV charging is not required. Therefore, electricity consumption and associated costs during weekends remains the same for all EV operation modes. However, if EV is used for any outdoor activities, this will incur additional costs for EV charging. It can be observed from Figure 6 that the total energy consumptions per day with EV in V2H + G2V and G2V only are very similar. This implies existing contracted power for G2V from the utility is sufficient to operate EV in V2H. Therefore, no upgrade of the contracted power is required and it avoids additional costs of implementing V2H. Moreover, due to lower energy price in off-peak periods and lower energy consumptions in on-peak pricing periods result EV as V2H + G2V to provide better economical outcome than EV as G2V only.

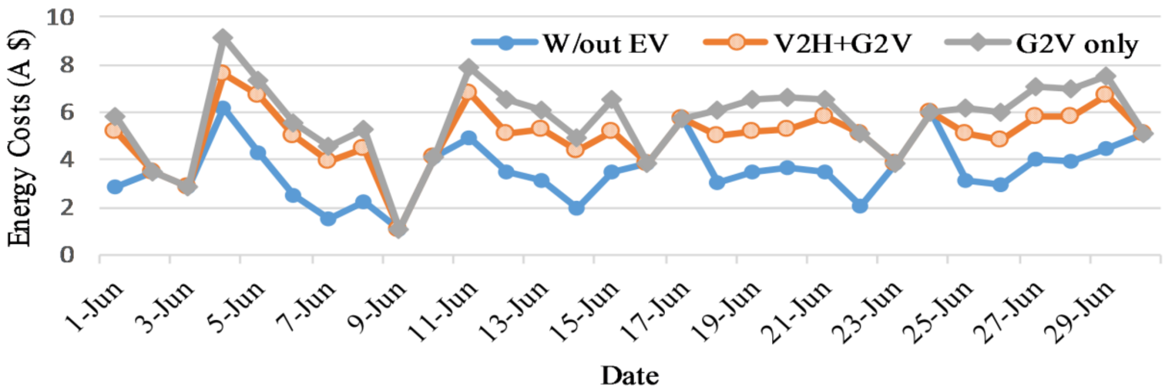

Figure 5 Daily energy costs in without EV and with different EV operation modes

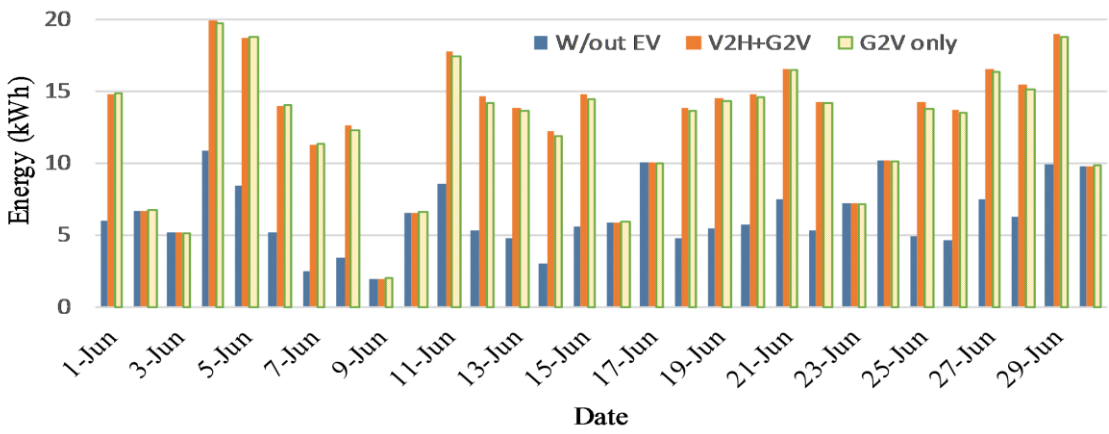

Figure 6 Total daily energy consumptions in different EV operation modes for a month

7. CONCLUSION

EV is acknowledged as one of the key variable load to increase operational flexibility and maximising economic benefit in HEMS. In this paper, an energy pricing regulated EV charging/discharging strategy is proposed in HEMS to maximise the economic benefit of EV. Three different EV operating modes are proposed, V2H and G2V are selected for economic benefit as currently G2V from EV is not commercially available in the proposed energy market. Comparative economic benefits of no EV, EV as V2H and G2V only are presented. The main findings of the study are:

- It is observed that EV participating in V2H during peak energy pricing periods exhibits a significant price reduction in daily and monthly electricity bills. About 11.6% reduction in monthly electricity bills is visible for using EV as V2H + G2V compared to EV as G2V only.
- More importantly, the power/energy profile of the house in V2H+G2V and G2V only is nearly the same. This avoids upgrade of the contracted power and implies no additional costs of implementing V2H.
- V2H provides better economic benefits over G2V only due to the differences in various pricing of purchasing electricity at different times of the day.

Considering renewable energy integration, coordinated control of EV and other storage systems in HEMS, and economic benefit of their operation and control will get further attention in future work. In addition, reliability assessment of the proposed HEMS will be the focus of future work.

Reference

1. Akorede MF, Hizam H, Pouresmaeil E. Distributed energy resources and benefits to the environment. *Renew and Sustain Energy Rev.* 2010;14(2):724-734.

2. Badea G, Felseghi R, Aschilean I, et al. Energen System for Power Supply of Passive House: Case Study. in 2015 Second Int Conf on Mathematics and Computers in Sciences and in Industry (MCSI), Malta, 2015:24-31.

3. Guan X, Xu Z, Jia QS. Energy-Efficient Buildings Facilitated by Microgrid. IEEE Trans. on Smart Grid. 2010;1(3):243-252.

4. Shakeri M, Shayestegan M, Abunima H, et al. An intelligent system architecture in home energy management systems (HEMS) for efficient demand response in smart grid. Energy and Buildings. 2017;138:154-164.

5. Tan KM, Ramachandaramurthy VK, Yong JY. Integration of electric vehicles in smart grid: A review on vehicle to grid technologies and optimization techniques. Renew and Sust Energy Reviews. 2016;53:720-732.

6. Administration UEI, Annual Energy Outlook 2011: With Projections to 2035. www.pseudology.org/gazprom/EnergyOutlook2011.pdf (Accessed on 29/08/2018).

7. Mwasilu F, Justo JJ, Kim EK, et al. Electric vehicles and smart grid interaction: A review on vehicle to grid and renewable energy sources integration. Renew and Sust Energy Rev. 2014;34:501-516.

8. Kara EC, Macdonald JS, Black D, et al. Estimating the benefits of electric vehicle smart charging at non-residential locations: A data-driven approach. Applied Energy. 2015;155:515-525.

9. Erdinc O, Paterakis NG, Mendes TD, et al. Smart household operation considering bi-directional EV and ESS utilization by real-time pricing-based DR. IEEE Trans. on Smart Grid. 2015;6:1281-1291.

10. Aziz M, Oda T, Mitani T, et al. Utilization of Electric Vehicles and Their Used Batteries for Peak-Load Shifting. Energies. 2015;8(5):3720-3838.

11. Shemami MS, Alam MS, and Asghar MSJ. Load shedding mitigation through plug-in electric Vehicle-to-Home (V2H) system. in 2017 IEEE Transp Electr Conf and Expo (ITEC). 2017:799-804.

12. Shin H and Baldick R. Plug-In Electric Vehicle to Home (V2H) Operation Under a Grid Outage. IEEE Trans. on Smart Grid. 2017;8(4):2032-2041.

13. Xu NZ and Chung YC. Reliability Evaluation of Distribution Systems Including Vehicle-to-Home and Vehicle-to-Grid. IEEE Trans on Power Systems. 2016;31(1):759-768.

14. Li C, Luo F, Chen Y, et al. Smart home energy management with vehicle-to-home technology. in 2017 13th IEEE Int Conf on Control & Automation (ICCA). 2017:136-142.

15. Naghibi B, Masoum MAS and Deilami S. Effects of V2H Integration on Optimal Sizing of Renewable Resources in Smart Home Based on Monte Carlo Simulations. IEEE Power and Energy Technology Systems Journal. 2018;5(3):73-84.

16. Paterakis NG, Erdinç O, Pappi IN, et al. Coordinated Operation of a Neighborhood of Smart Households Comprising Electric Vehicles, Energy Storage and Distributed Generation. IEEE Trans on Smart Grid. 2016;7(6):2736-2747.

17. Wu X, Hu X, Yin X, et al. Stochastic Optimal Energy Management of Smart Home With PEV Energy Storage. IEEE Trans on Smart Grid. 2018;9(3):2065-2075.

18. Erdinc O, Paterakis NG, Mendes TDP, et al. Smart Household Operation Considering Bi-Directional EV and ESS Utilization by Real-Time Pricing-Based DR. IEEE Trans on Smart Grid. 2015;6(3):1281-1291.

19. Rastegar M, Firuzabad MF, and Aminifar. Load commitment in a smart home. Applied Energy. 2012;96:45-54.

20. Berthold F, Ravey A, Blunier B, et al. Design and Development of a Smart Control Strategy for Plug-In Hybrid Vehicles Including Vehicle-to-Home Functionality. IEEE Transactions on Transportation Electrification. 2015;1(2):168-177.

21. Alahyari A, Fotuhi FM and Rastegar M. Incorporating Customer Reliability Cost in PEV Charge Scheduling Schemes Considering Vehicle-to-Home Capability. IEEE Transactions on Vehicular Technology. 2015;64(7):2783-2791.

22. Rebecca G, Charles D, Paul R, and Chris W. Vehicle-to-grid feasibility: A techno-economic analysis of EV-based energy storage. Applied Energy. 2017;192:12-23.

23. Li Y, Zhou H, Ma X, and Wang H. Economic Analysis of Different Electric Vehicle Charging Scenarios. IOP Conf Series: Mat Sci and Eng. 2017;199(1): 012041.

24. Datta U, Kalam A, and Shi J. Electric Vehicle (EV) in Home Energy Management to Reduce Daily Electricity Costs of Residential Customer. Journal of Scientific and Industrial Research. 2018;77(10):559-565.

25. Cao C, Chen B.Generalized Nash equilibrium problem based electric vehicle charging management in distribution networks. Int J Energy Res. 2018;1–13.

26. Luca de Tena D, Pregger T. Impact of electric vehicles on a future renewable energy-based power system in Europe with a focus on Germany. Int J Energy Res. 2018;42:2670–2685.

27. Australian Energy Regulator, https://www.aer.gov.au/system/files/ACIL%20Allen%20Energy%20benchmarks%20report%202017%20-%20updated%205%20June%202018.pdf (Accessed on 17/09/2018).

28. Ozansoy C ,Ustun TS, and Zayegh A. Experience and Applications of Electric and Plug-in Hybrid Vehicles in Power System Networks; in Veneri, O. (ED.), Technologies and Applications for Smart Charging of Electric and Plug-in Hybrid Vehicles. Springer Int Publishing, Cham. 2017:243-280.

29. Australia Bureau of Statistics. Energy Consumption Benchmarks http://www.abs.gov.au/AUSSTATS/abs@.nsf/Lookup/4102.0Main+Features40July+2013.

30. Electric Vehicle Council. The state of electric vehicles in Australia. https://climateworks.com.au/sites/default/files/documents/publications/climateworks_australia_state_of_electric_vehicles2_june_2018.pdf (Accessed on 17/09/2018).

31. AEMO insights. Electric Vehicle. https://www.aemo.com.au/Media-Centre/~/-/media/5A0AB3A41BC8468BBB97A1C79E8AD1BA.ashx (Accessed on 17/09/2018).

32. Australia Bureau of Statistics. Household and Family Projections. http://www.abs.gov.au/ausstats/abs@.nsf/Latestproducts/3236.0Main%20Features42011%20to%202036 (Accessed on 17/09/2018).

33. Speidel S, Jabeen F, Olaru D, Harries D, and Bra¨unl T. Analysis of western Australian electric vehicle and charging station trials. Aust Transp Res Forum 2012;1:1–12.

34. ABC (2012) New charge point pops up as electric car trial continues. [cited 2014 23 May]. http://www.abc.net.au/local/stories/2012/06/14/3525454.htm

35. Nissan, http://www.nissan.com.au/-/media/files/brochures/models/leaf/charging_v2.ashx (Accessed on 23/10/2018).

36. Origin Energy, https://www.originenergy.com.au/content/dam/origin/residential/docs/energy-price-fact-sheets/vic/VIC_Electricity_Residential_Powercor_Origin%20Supply.PDF (Accessed on 25/08/2018).