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The electricity demand of an EV providing power via vehicle-to-home and its potential impact on the grid with different electricity price tariffs

Donovan Aguilar-Dominguez*, Alan Dunbar, Solomon Brown

Department of Chemical and Biological Engineering, Mappin St, Sheffield, S1 3JD, United Kingdom

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Abstract

Electricity demand is expected to grow in the upcoming years due to the electrification of transport, which will likely result in an increase in electricity peak demand when charging at home; this would not represent a problem for the electric vehicle (EV) owner but could potentially destabilise the grid. This work has compared the use of stationery and vehicle-to-home (V2H) energy storage systems to minimise the electricity bill for the household consumers. The impact of using different electricity tariffs and the peak demand derived by this was also investigated. Real-world data was used to model the availability of the EVs to provide V2H during the day. Constraints to guarantee adequate charging of the EV to ensure the ability to provide transportation have been implemented. Two different stationary batteries and two EVs were used for the simulations. High peaks on the demand of up to 6 kW per vehicle (the bi-directional charger's maximum capacity) and up to 5 kW (the batteries charger's maximum capacity) are expected every time that the electricity price drops, and low peaks are expected when the electricity price increases. Moreover, high peaks are expected mostly at night when the electricity price tends to be cheaper and/or after driving the EV and plug it again to charge, however the model will try to constraint the charging of the EV until the price is low again unless there is a journey likely to happen in the near future. The combination of PV generation with a stationary battery or a V2H technology can produce savings of at least 30% regardless the electricity tariff and a reduction of up to 85% in the electricity bill can be achieved under the Time-of-day tariff. The results give a perspective of what can the grid expect when charging an EV at home during winter.

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Keywords: Battery; Electric vehicle; Energy storage; Electrical grid; Electric demand; Vehicle-to-home

1. Introduction

Future energy scenarios predict that electricity demand will grow by 2030, in part, due the electrification of transport [1]. Considering that most vehicles are parked 95% of the time [2], EVs can be connected to the grid and

* Corresponding author.
E-mail address: daguilardominguez1@sheffield.ac.uk (D. Aguilar-Dominguez).

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support it by both providing energy stored within them during times of peak demand and storing surplus energy generation [3]. They also have the potential to provide energy directly to a household via vehicle-to-home (V2H), which is a system that allows the consumer to supply the house with the energy stored in the vehicles' battery at periods of high price [4].

Liu et al. [5] discussed different methodologies and approaches for integrating electric vehicles into the grid including V2H among other technologies. They found that uncontrolled home charging of EVs has significant impact on the local grid. Tuttle et al. [6] studied the use of V2H capable vehicles to deliver backup power to a house in case of an outage finding that a V2H system coupled with PV generation can provide up to 600 h of backup power to the house. Turker et al. [7] proposed a housing peak shaving algorithm for V2H and V2G technologies and found that these technologies can minimise the ageing rate of an MV/LV transformer and help to maintain the voltage quality of the energy supplied. Nguyen and Le [8] considered a home energy scheduling model using V2H to minimise the electricity bill related to providing heat to a household in the US. They found that their proposed model reduced the electricity cost significantly and also reduced the energy demand on the local grid. Berthold et al. [9] included data from photovoltaic (PV) generation and wind production in order to minimise the electricity cost for the house and reported total energy costs savings of up to 20%. Ma et al. [10] proposed a control strategy that takes advantage of the electricity price when charging and discharging the EV via V2G finding that vehicle owner's costs are reduced roughly by half when using V2G, however they did not considered the impact of the driving behaviour in the state of charge of the batteries in their study and they did not study V2H applications.

No previous studies have considered the demand-from-the-grid profile predicted when the reduction of the consumer electricity cost is the main goal using different electricity tariffs and V2H is used to provide energy to the house taking into account the EV availability. This is what this paper aims to do, while also considering PV generation from panels at the house. A comparison between the use of a stationary battery and a V2H energy storage system to minimise the electricity bill for the household consumers has been explored. The impact of different electricity tariffs on this and the peak demand was also investigated.

2. Methods

In this study the electricity consumption data [11] for a household in London and PV generation readings [12] for a Greater London Household from the UK Power Networks project is considered. The household modelled has a 3.5 kWp PV system. Fig. 1 shows the household electricity demand profile and the PV generation profile for 2 weeks in winter with a 30-min resolution. Transport data taken from the UK's National Travel Survey (NTS) [13] was used to model vehicle use and availability.

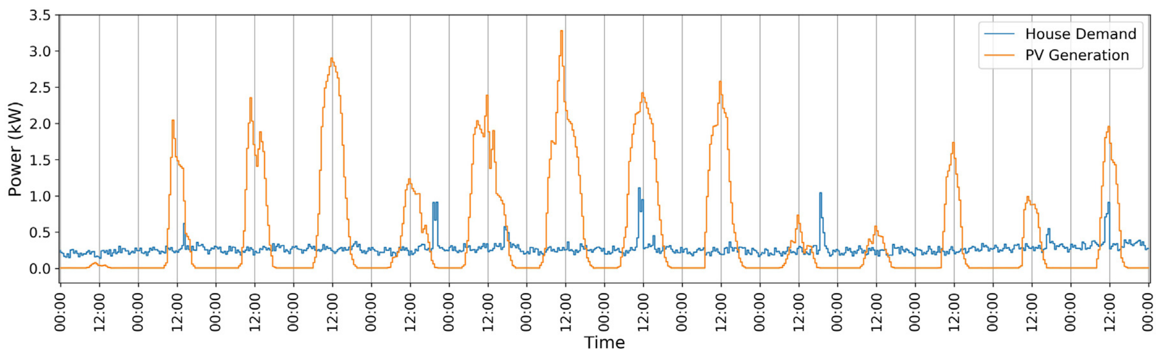

Fig. 1. Demand and PV generation profile of the house for 14 days.

Fig. 2 shows the EV availability profile derived from the NTS by assuming that when the vehicle is available (i.e. not travelling) it is connected to the house and when is not available is travelling on an average journey of 8.2 miles during each 30 min it is unavailable. This as the average journey distance found in the NTS. Most journeys in the NTs were shorter than 30 min time step being used in the analysis. Therefore, the vehicle is assumed to be unavailable for at least one entire time step per journey. The NTS dataset only provides seven days of data for each user, therefore, to generate an availability profile for two weeks the data for one week was duplicated.

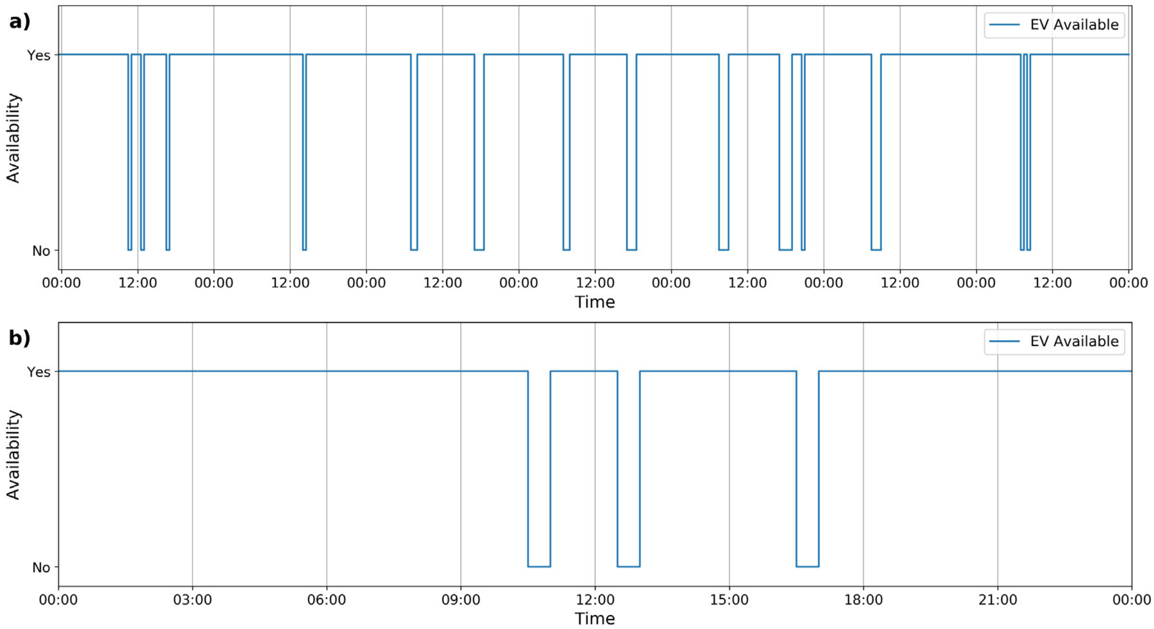

Fig. 2. (a) Availability profile for 7 days. (b) Availability profile for 24 h.

Four different tariff structures were considered. The first was a flat residential tariff [14], where price for the energy consumed is the same no matter the time of the day. The second was an Economy 7 tariff [14], with seven hours of cheaper electricity price during 11:00 pm and 06:00 am and a higher price for the rest of the day. The third was a time-of-day tariff [15] where smart meters are used to enable the power provider to charge a different tariff according to the time of the day. Finally, a wholesale tariff, which simulates a dynamic tariff that follows the energy trade market in the UK [16], was collected with 1-hour resolution and then oversampled to 30-min resolution to fit the dataset was used. It should be noted that this last wholesale tariff is not currently available to individual consumers.

A house was modelled which has either a battery providing storage and power to the house, or an EV that charges and powers the house when it is not being used for transport. In order to reduce the consumers' electricity bill to a minimum, the model determines the optimal charging–discharging schedule of the battery or EV. The optimisation model proposed by Barbour and Gonzalez [17] shown in Eq. (1) that evaluates the electricity cost at each period is used.

$$cost\ (t) = [d\ (t) - sg\ (t) + es\ (t)]\ \Delta t \pi\ (t) \tag{1}$$

$d\ (t)$ is the user's battery input/output profile where positive demand values represent energy drawn from the grid to charge the battery and negative demand values represents the energy storage system providing electricity to the house. In the case of the EVs, consumption from travelling when not available is also represented as negative values in this profile, i.e. a power output but which in this case does not contribute to meeting the household electricity demand, instead providing transportation. sg (t) is the solar generation, es (t) is the charge or discharge action of the battery or EV $\pi(t)$ is the electricity price at that period. t refers to functions that vary with time. As it is assumed that there is no payment if excess solar energy is exported to the grid, the following conditions apply as shown in Eqs. (2) and (3), where π^{ex} for this study is 0.

$$\text{If} \quad d\ (t) + es\ (t) \geq sg(t)$$
$$cost\ (t) = [d\ (t) - sg\ (t) + es\ (t)]\ \Delta t \pi(t) \tag{2}$$
$$\text{If} \quad d\ (t) + es\ (t) < sg(t)$$
$$cost\ (t) = [d\ (t) - sg\ (t) + es\ (t)]\ \Delta t \pi^{ex} = 0 \tag{3}$$

The objective function shown in Eq. (4) represents the consumer's total electricity cost over the studied period.

$$\min \sum_{t=0}^{t=N} cost\ (t) \tag{4}$$

The minimisation is constrained by the physical limits of the battery or EV, given by Eq. (5). The State of Charge (SOC) of the system is described in Eq. (5), where $P(t)$ is the charging or discharging power of the battery or EV considering the actual charge/discharge efficiency of the battery or EV. Δt is the time interval between readings in the dataset, which in this case is 30 min. Eqs. (6)–(9) represent other constraints to the model.

$$SOC\ (t) = SOC\ (t-1) + \Delta t P(t) \tag{5}$$

$$SOC^{min} \leq SOC\ (t) \leq SOC^{max} \tag{6}$$

$$P^{min} \leq P\ (t) \leq P^{max} \tag{7}$$

If $P\ (t) \geq 0$, charging.

$$es\ (t) = \Delta t P\ (t)\, \eta = \Delta SOC(t) \tag{8}$$

If $P\ (t) < 0$, discharging.

$$es\ (t) = \Delta t P\ (t)\, \eta = \Delta SOC(t) \tag{9}$$

$SOC\ (t)$ is the state of charge of the battery or EV at any time period. The SOC^{min} and SOC^{max} constraint parameters are shown in Table 1 and were applied to ensure longevity of the batteries. In order to compare EVs and household batteries, this constraint was implemented for both systems. P^{min} and P^{max} are the minimum and maximum rate at which the battery or EV discharge and charge. η is the efficiency rate of the battery or EV assuming that charge and discharge efficiency are the same. $\Delta t P\ (t)\, \eta = \Delta SOC(t)$ is the amount of energy added or removed from the battery or EV in a time Δt.

Table 1. Constraint parameters for the state of charge.

Minimum SOC limit (SOC^{min})	10%
Maximum SOC limit (SOC^{max})	85%

This model was then used for the simulation of two different batteries and two different vehicles, as shown in Tables 2 and 3 respectively. The Nissan Leaf 2018's charge/discharge efficiency of 93% was also used for the Mitsubishi Outlander as no information about the efficiency was found for the latter. The Tesla Powerwall 2's charge/discharge efficiency of 90% was also used for the Nissan/Eaton battery as no information about the efficiency was found for the latter. A fast-charging V2H enabled charger was considered for the EV simulations, with a bi-directional power flow up to 6 kW [18]. The optimisation problem was formulated and solved using the Pyomo framework [19] and the Gurobi optimisation solver [20]. Pyomo is a python-based open-source software package for formulating optimisation models.

Table 2. Batteries parameters for analysis in this paper.

Name	Capacity (kWh)	Battery power (kW)	Charge/discharge efficiency	Battery type
Nissan/Eaton [21]	6.75	3.68	90%	Stationary
Tesla Powerwall 2 [22]	13.5	5	90%	Stationary

Table 3. Electric vehicles parameters for analysis in this paper.

Name	Capacity (kWh)	Battery power (kW)	Charge/discharge efficiency	Vehicle type
Mitsubishi Outlander [23]	13.8	6	93%	PHEV
Nissan Leaf 2018 [24]	38	6	93%	All electric

3. Results

By optimising the charging schedule to reduce the electricity bill, an increase in the demand of up to 6 kW in the case of the EVs due to the bi-directional charger limitations was observed. In the case of the household batteries, this peak demand will be limited by the charging power of each battery, reaching up to 5 kW in the case of the Tesla Powerwall 2 battery.

Figs. 3 and 4 present the power input/output for the battery, given the optimal scheduling of the battery utilised, using the flat and economy 7 tariff respectively. As shown in Fig. 3, with the flat tariff the maximum charging (positive power in (a) and increasing SOC in (b)) happens around midday when PV generation is available. This demand profile has low demand peaks that does not surpass 2 kW. In this case, the battery stops charging when the SOC gets to the lower limit 10%. Comparing this to Fig. 4, a clear difference in the peak demand when charging can be seen with economy 7 tariff, where the model shows the battery charging both when PV is available and also when the electricity price is low at night. The peak demand is limited by the max charge rate of each system.

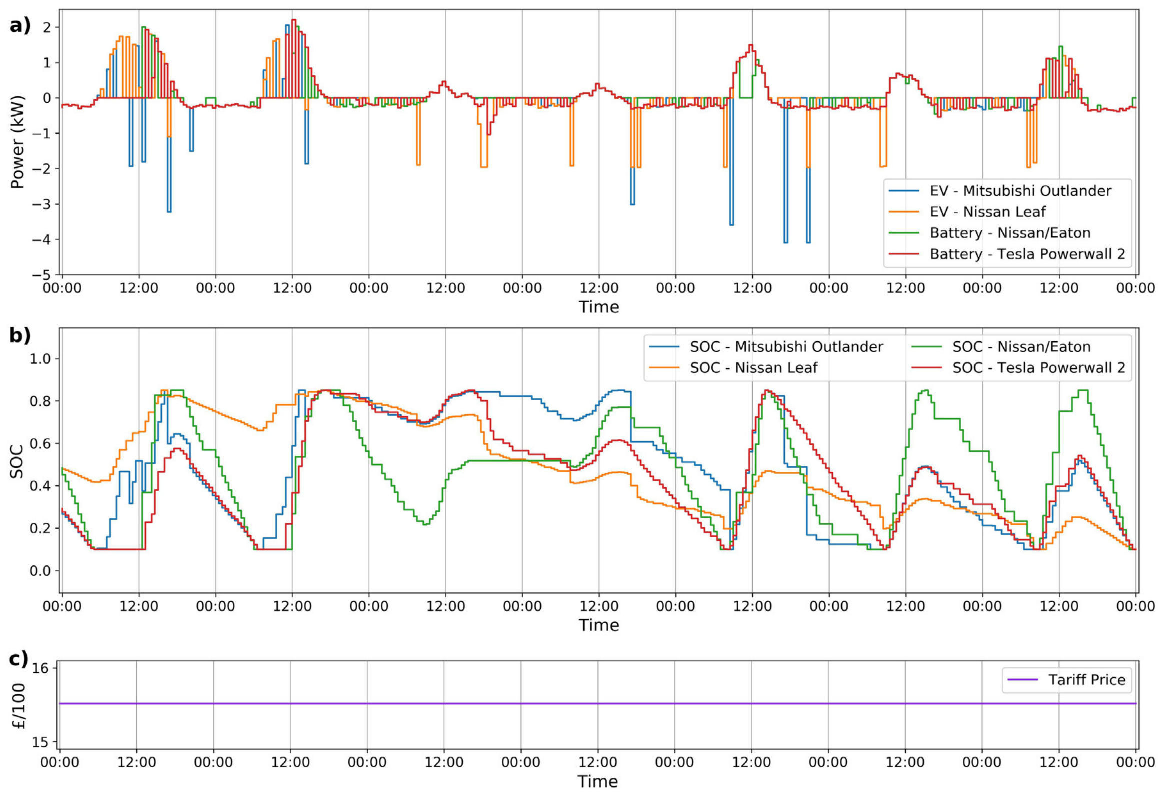

Fig. 3. Flat tariff for 7 days. (a) Input/output profile of the battery system. (b) SOC. (c) Tariff price.

Fig. 5, that corresponds to the resulting charge/discharge behaviour when using the time-of-day tariff shows peak demands of up to 6 kW (maximum charge limit for the EVs) and peak demands of up to 5 kW and 3.68 kW (maximum charge limit of the Tesla Powerwall 2 and Nissan/Eaton, respectively) when the electricity price is cheaper at night, with a low demand most of the days during the morning and afternoon due to the increase on the electricity price. The SOC under this tariff stays over 40% for almost three days in a row in the case of the EVs. For the batteries, the SOC stays over 40% for over one day. The wholesale tariff in Fig. 6 shows demands of up to 6 kW (maximum charge limit for the EVs) and peak demands of up to 5 kW (maximum charge limit of the Tesla Powerwall 2) in mid-afternoon and during the night when prices are lower on almost every day due to the dynamic changes of the electricity prices. With this tariff, charging at night is not as common as with the two previous tariffs due to high levels of SOC on most of the days. The dynamic change of the electricity price results in fewer high peaks in the demand during most of the week when compared to economy 7 and time-of-day tariffs. Moreover,

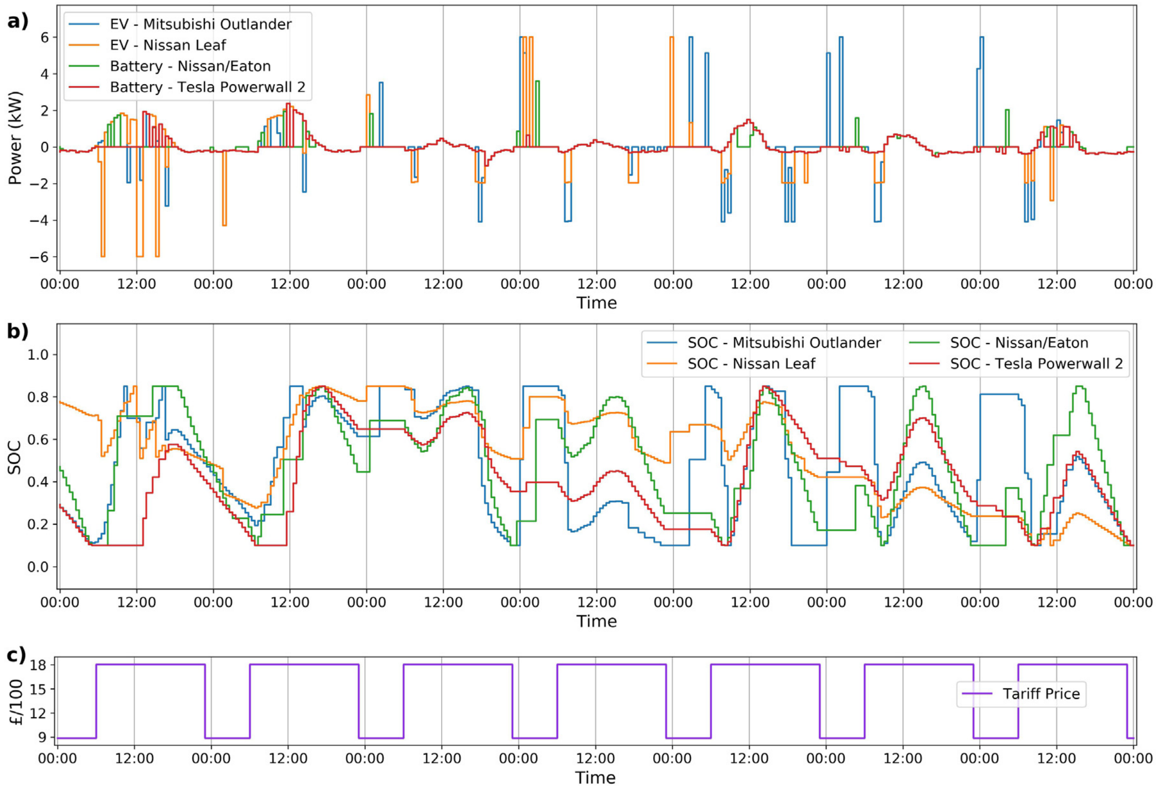

Fig. 4. Economy 7 tariff for 7 days. (a) Input/output profile of the battery system. (b) SOC. (c) Tariff price.

the flat tariff is the tariff that produced even fewer peaks in demand from all the tariffs due to the fixed electricity price during the day. Fig. 7 shows the optimal net demand of the house produced when using each energy storage device analysed in this study.

As the main goal of the optimisation model is to minimise the consumers' electricity bill, Tables 4 and 5 show the total electricity cost when using the household batteries and the total electricity cost when using the EVs, respectively.

Table 4. Total cost of the electricity for the house when using the batteries.

Tariff	No battery (£)	Nissan/Eaton (£)	Tesla Powerwall 2 (£)
Flat	16.40	8.19	4.86
Economy 7	14.87	5.24	2.96
Time-of-day	10.26	2.93	1.63
Wholesale	16.75	6.26	3.20

Table 5. Total cost of the electricity for the house when using the EVs with and without V2H.

Tariff	Mitsubishi Outlander		Nissan Leaf 2018	
	V2H (£)	No V2H (£)	V2H (£)	No V2H (£)
Flat	30.36	46.11	9.53	28.33
Economy 7	25.73	49.45	5.90	28.76
Time-of-day	17.71	39.12	3.25	22.08
Wholesale	26.95	50.57	6.27	30.47

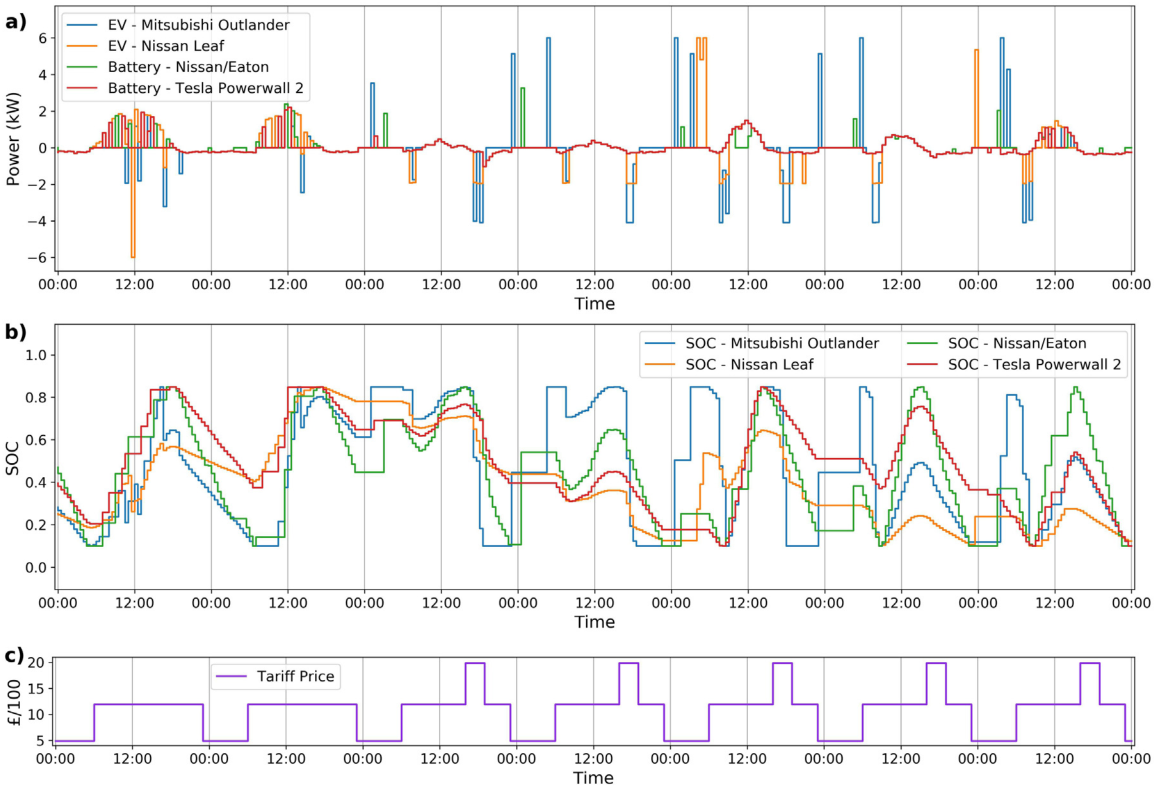

Fig. 5. Time-of-day tariff for 7 days. (a) Input/output profile of the battery system. (b) SOC. (c) Tariff price.

4. Discussion

The results showed that Economy 7 and Time-of-the-day tariffs are the ones that put most strain on the grid with more peaks in the demand during the week due to their low electricity cost at certain times of the day. Also, these two tariffs resulted in the lowest electricity price for both EVs and batteries because the model took advantage of the low cost of power. Moreover, the Time-of-day tariff resulted in the best tariff for the consumer with the lowest electricity cost for both EVs and batteries, this can be due to the model avoiding the high price during the weekdays prioritising the charge when the electricity price is low. The flat tariff resulted in the smoothest demand because the electricity prices do not change during the day. However, this tariff presented the highest electricity cost of all the tariffs analysed due to the fixed electricity price during the day. The wholesale tariff is somewhere in between the other tariffs, it presents high peaks on the demand when prices are low and low peaks on the demand when prices are high due to the high frequency changes in electricity price with a total electricity cost a little bit higher than the electricity cost when using Economy 7 tariff. The addition of PV generation makes the model prioritise the charging state of both EVs and stationary batteries when the energy generated surpasses the demand of the house at midday.

The use of a V2H enabled charger can reduce the electricity bill by up to 85% with the Nissan Leaf 2018, compared to just charging the EV without using V2H and the Time-of-use tariff. A minimum of 30% reduction in the total electricity price can be achieved while using V2H regardless the tariff or EV used, compared to just charging the EV without using V2H. Moreover, a 50% reduction in the total electricity cost is expected when adding a battery to the household regardless of the tariff or battery used, with up to 85% reduction when using the Tesla Powerwall 2 and the Time-of-use tariff when compared to not using a battery.

For all the tariffs analysed in this paper the SOC behaviour of the Nissan Leaf 2018 is similar to the Tesla Powerwall 2, where the Tesla Powerwall 2 presents a steeper charge and discharge behaviour due to its lower energy storage capacity when compared to the Nissan Leaf 2018.

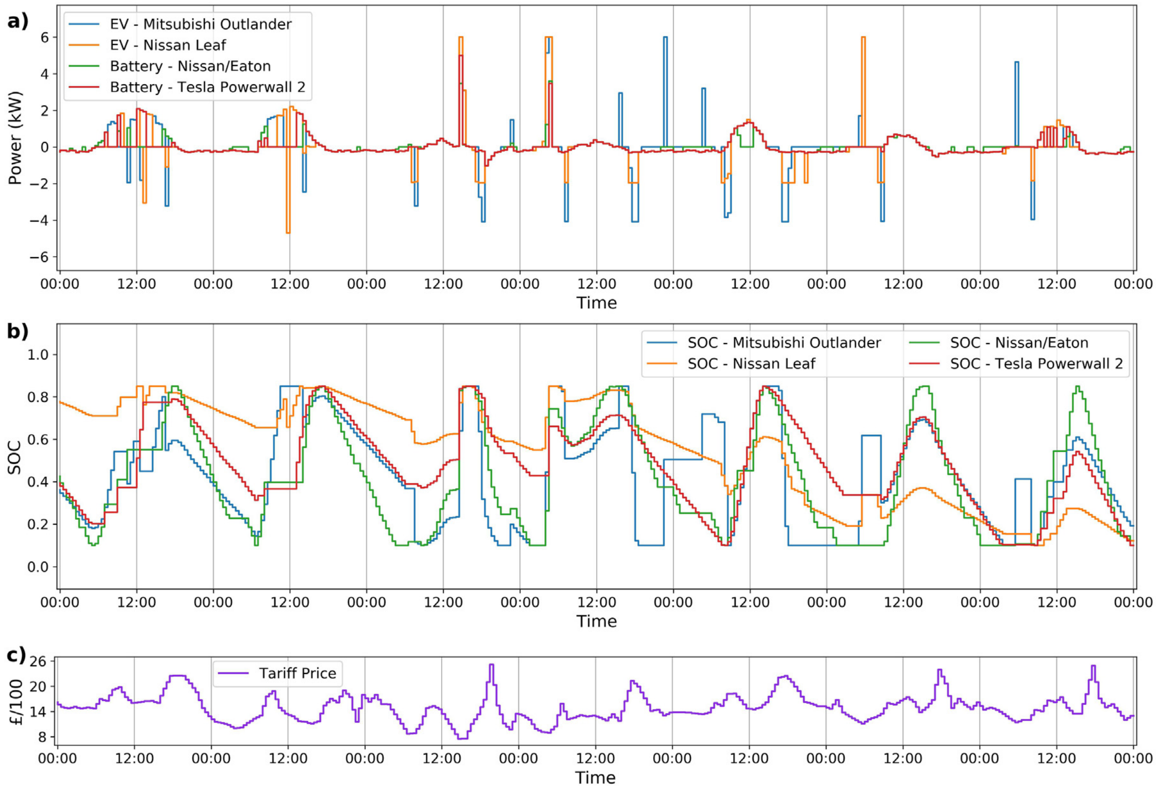

Fig. 6. Wholesale tariff for 7 days. (a) Input/output profile of the battery system. (b) SOC. (c) Tariff price.

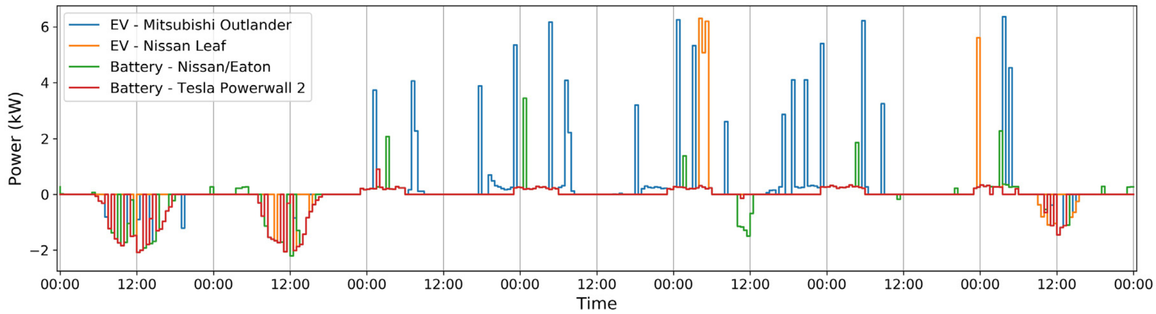

Fig. 7. Input/output profile of the house for the time-of-day tariff.

5. Conclusion

This work has compared the use of stationary batteries and V2H energy storage systems to minimise the electricity bill for the household consumers. The impact of different electricity tariffs on this and the peak demand was also investigated.

Savings of up to 85% can be achieved during winter when using an EV to provide power to a household via V2H with a minimum 30% reduction regardless the EV or tariff used.

High peaks in the demand are expected every time that the electricity price drops, and low demand is expected when the electricity price increases. Moreover, high demand peaks are more likely to happen at night when the electricity price is low and when a journey is expected to take place in a couple of hours in the future so the EV can have the adequate SOC to complete its journey. This may have implications for power providers should V2H be adopted on a large scale.

The maximum power rating of the charger is important as it determines the maximum peak demand when charging an EV which could potentially destabilise the grid if V2H is adopted on a large scale. On the other hand, home batteries draw energy from the grid without raising the demand too high because their charge peak power is lower in comparison to EVs.

The presence of PV generation when sunlight is available results in the model prioritising the charging state of the batteries for both stationary batteries and EVs when the vehicle is available and the energy generated surpasses the demand of the house.

Uncertainty in the demand on the grid is expected since it is hard to predict driving behaviours, however, the results give a good perspective of what can the grid expect when charging an EV at home for the winter season.

Further work on this topic should focus on the self-sufficiency of a household when using V2H services while guaranteeing the main purpose of a vehicle and the addition of more availability profiles.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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