

Evaluating the Benefits of Vehicle-to-Grid in a Domestic Scenario

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Abstract

The majority of EV charging in the UK currently occurs at home, suggesting domestic installations will represent a significant portion of the future vehicle-to-grid market. This paper evaluates the potential benefits; both economic and technical, in utilizing an existing electric vehicle battery asset through vehicle-to-grid, over the installation of static battery storage. A domestic property in Loughborough is used as a case study, which has 4kWp photovoltaics, 2kWh static battery storage installed and a Nissan Leaf.

The greatest limiting characteristics of both the static storage and V2G systems is the fixed rate converter, being 500W and 3kW respectively. Due to the low electrical demand of the house, these converter rates cause the majority of the demand to be exported back to the grid, with the V2G unit simulated to export over 1000kWh per annum to the grid, suggesting market value stacking is necessary. With a variable rate converter, the cost savings for the property increase from £95 per annum to over £300, and the PV utilisation rate increased by 12%.

Key Words: V2G, efficiency, energy storage

1 Introduction

Photovoltaics (PV) make up the majority of the renewable electricity micro-generation in the UK, with over 870,000 systems under 3kW in size installed by the end of the third quarter of 2016 [1]. Battery storage can help to offset demand during peak hours and research of battery storage in combination with renewable generation is widespread [2]–[6]. Storage in combination with PV is said to increase the usability of the generation technology, storing excess electricity during the day to re-distribute during peak demand [7,8]. As specified by Leicester et al. [9], self-consumption is defined as the proportion of energy generated on-site which is used to do work on-site as opposed to being exported [10]. They go on to identify the following reasons as to why this is important:

- (i) 'Influence on the economic viability of consumer co-located PV.
- (ii) Direct impact on the low- and medium-voltage electricity grid.
- (iii) Supports decision makers in the appropriate design of PV-related regulatory and fiscal policy mechanisms.' [9]

Vehicle-to-Grid (V2G) allows electric vehicles (EVs) to act as battery stores whilst stationary, providing energy back to buildings or the grid through a bi-directional converter. The suggested benefits of utilising

EVs as battery storage is the management of energy loads within local networks and the provision of EVs for peak shaving services for National Grid (NG) [11]–[14]. Management of fixed asset storage is fairly easy to regulate, however EVs pose additional variables found with standalone systems such as vehicle use, journey requirements and location [15]–[17]. Using EVs for this purpose potentially reduces the impact of increased charging on the electricity grid as the numbers of EVs increase [18]. In addition, the cost of the battery storage is negated and the EV can be appropriately managed to ensure charging and discharging occurs during times of excess on-site generation or low network demand.

This paper uses real-world data from a domestic property test pilot to evaluate the economic and operational benefits of V2G over static battery storage. Potential economic savings occur from the battery cost and alignment of property electricity demand with vehicle availability. The paper takes a data analysis approach, using the existing data collected from the property and a stochastic modelling approach, through which the inclusion of a V2G unit is considered and compared with the existing battery operation. The configuration of the energy systems within the building are first described, before the methodology for data collection and V2G operation modelling. Finally, analysis and discussion of the results before the conclusions and final work are presented.

2 Building Demand and System Configuration

This research compares two battery storage systems based on a number of economic, technical, operational and environmental criteria. The economic analysis and market potential is carried out using a stochastic modelling approach based on the methodology described by Gough et al. [19] and builds on previous work carried out by [20]. Due to the data-driven approach of the modelling, real-world data from a domestic property can be evaluated, including; vehicle usage, building demand, PV generation and battery storage data.

2.1 The Property

The domestic property evaluated in this paper is in Loughborough, Leicestershire, UK and is a three-bedroom detached house with an occupancy of two adults and two young children. Approximate floor area is 83m² and the EPC rating is band C, giving it an efficiency rating of between 69-80% [21]. The data collected within the building from the various energy systems is given in Table 1, with the system configuration given in Figure 1. This is the same property used in the analysis in [22], in which the operation of the existing battery storage solution is studied in detail with relation to its techno-economic performance.

Table 1: Property data collection and technology specification [22]

	Specification	Data Collected	Units	Frequency
PV Array	4kW monocrystalline PV array (20.4% efficiency, 327W nominal power rating)	Solar generation Solar export to the grid House import House usage	kWh	5-minutes
Battery Storage	2kWh rated (1.6kWh actual); 400W converter; lithium-ion battery	SoC over time Energy flow in/out	% kWh	5-minutes
Building Demand		Energy flow in/ out	kWh	5-minutes

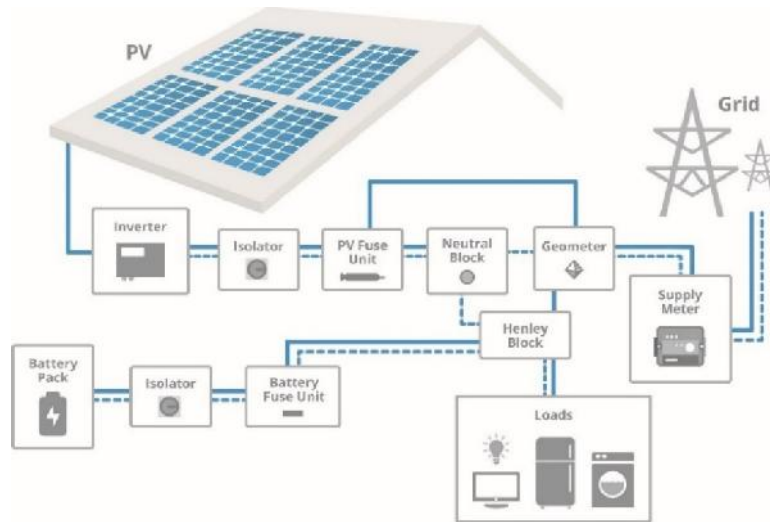


Figure 1: System schematic for domestic property with PV and static battery storage [22]

2.2 Electricity Demand and Supply

Annual electricity consumption for the property in 2016 was 4,142kWh, just over 1,000 kWh above the UK national average for properties on an Economy 7 tariff [23]. Figure 2 plots the electricity demand of the property against the PV generation per 5-minute period to produce the net demand for 05/07/16, which is 8.7kWh demand from the grid and 15.27kWh excess generation from the PV system. 75% of the energy generated by the PV system was exported to the grid, suggesting the system efficiency could be improved if a storage system were installed and operated to align with PV generation.

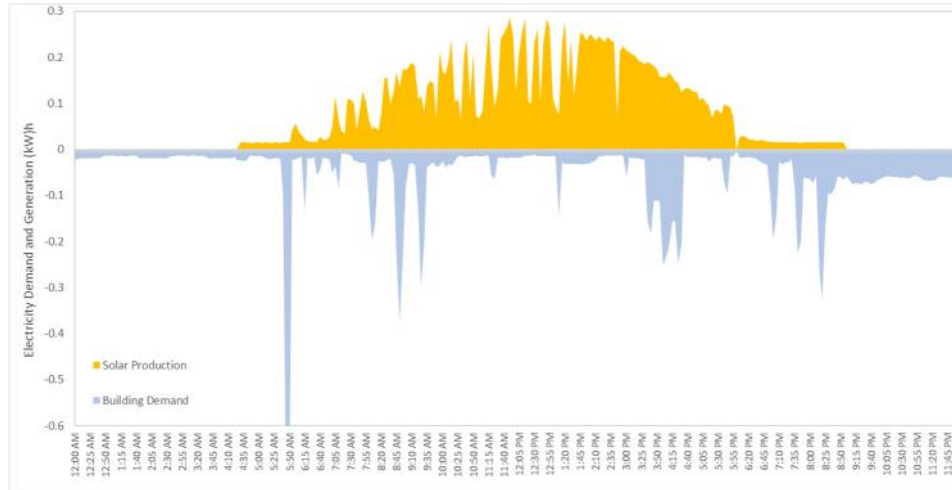


Figure 2: Area chart for an average July daily net building demand and PV generation per 5-minutes. Positive values are demand, negative is an excess of generation from the PV.

2.3 Impact of Battery Storage

The battery storage system is programmed to operate alongside the PV generation and property demand, charging when there is an excess of PV generation and discharging when electricity demand is highest. Figure 3 shows this operation for the same day as Figure 2. Due to the size of the battery, the charge and discharge amount is 1.247kWh and 1.246kWh respectively, which demonstrates the high efficiency rate of the system. As per Figure 3, all of the battery charging is performed from the PV generation and the system is discharged when there is a grid electricity demand from the property.

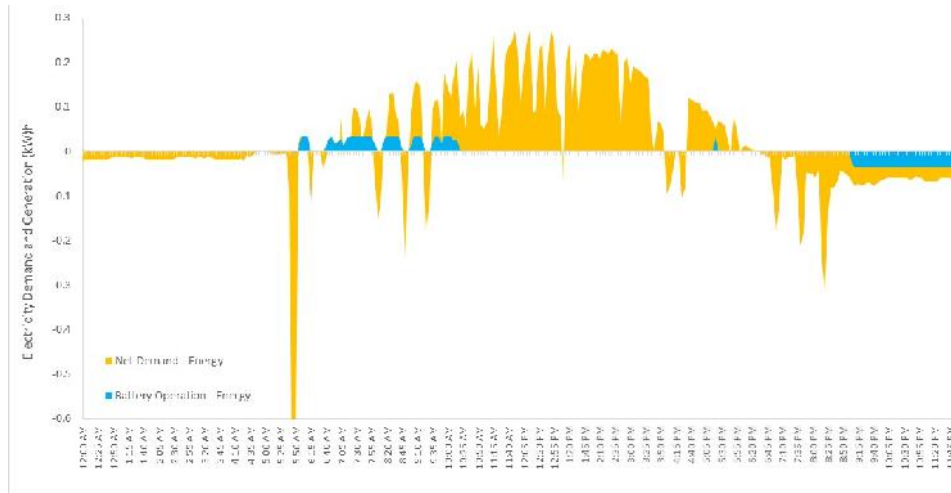


Figure 3: Stacked bar chart for average daily building demand and PV generation with the addition of battery storage operation. Positive values are demand, negative is an excess of PV generation.

Due to the operational cycle of the battery, it charges when the PV generation goes roughly over 400W, however doesn't appear to consider the net demand of the home. As a result, the property demand requirement from the grid actually increases, meaning the PV generation is not being utilised effectively and the property is importing additional electricity. This increases the import and export electricity amounts by 1kWh, suggesting the operational cycle of the battery needs to change in order to better meet the needs of the household.

3 Vehicle-to-Grid Techno-Economic Model

Simulation of the EV use and V2G availability is as specified by Gough et al. [19] and developed to include the domestic usage profile specified in Figure 2. Creation of an operation profile for the vehicle that considers both energy and time available for V2G services is separated into three processes; a) data collection and journey summary creation, b) SoC, location overlay analysis and profile creation and c) evaluation of profile with demand requirement to create a full operation profile. This process is part of a much larger suite of tools as depicted in Figure 4, which takes vehicle telemetry data through a drive cycle creator into an integrated vehicle model.

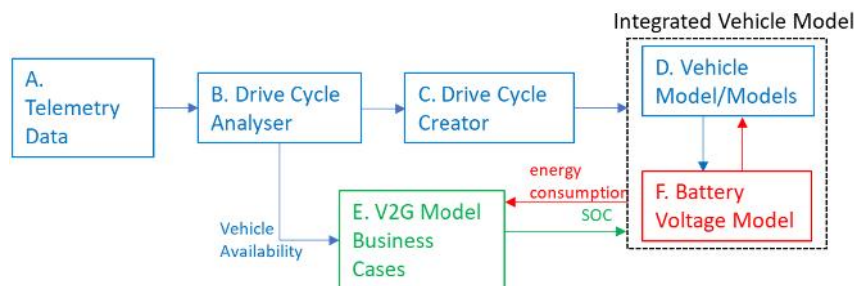


Figure 4: Whole system diagram of data collection and modelling environment for EVs and V2G scenario evaluation.

The approach for data analysis of the vehicle builds upon previous work conducted by the author [15, 24] and was adapted to work with a domestic use vehicle. EV usage data collected from an on-board telemetry system on the vehicle is specified in Table 2.

The information pathway is as follows;

1. Data collected from telemetry systems installed on the vehicles is provided in its raw format to the Drive Cycle Analyser.
2. Data summaries for vehicle journeys, charging events and vehicle availability are input in the V2G model for further simulation.

3. Data relating to vehicle journey information including GPS data, journey average speed, distance and micro-trip type are sent to the drive cycle creator.
4. The representative drive cycle is generated in the drive cycle creator and then fed into the vehicle model.
5. The vehicle model calculates the power flow to and from the battery during drive cycles.
6. The battery voltage model checks the ability of the battery to deliver or absorb power.
7. The energy consumption is then fed into the V2G model. The state-of-charge (SOC) of the battery is also fed into the V2G model prior to any V2G services.
8. The energy cost of the V2G cycle is also calculated as an output.

Table 2: Section of the telemetry data collected from a Nissan Leaf.

Signal name	Unit	Frequency
Absolute Time	yyyy-mm-dd hh:mm:ss:mmm	
Relative Time	hh:mm:ss:mmm	
GPS position	[lat lon] Degrees	
Drive Mode	Neutral/ Drive/ Brake/ Park	
Eco Mode Active	0/1	1-second
Speed	km/h	
Remaining range	km	
Current	A	
Voltage	V	
State of Charge	%	

3.1 Vehicle Availability Analysis

To establish the availability of the vehicle at the property for V2G and charging services, the GPS position data is combined with the journey summary data to extract the stationary and driving start and end location of the vehicle. The journey summary data has six event types as shown in Table 3.

Table 3: Journey summary event description for identification of stationary, driving or V2G events at the property.

Event type	Criteria
Drive	Vehicle is moving. If stopped, no longer than a limit time (2 mins).
Park	Vehicle stopped for more than a limit time (2 mins) and not charging or V2G.
Mode 2 charge	PWM (Pulse Width Modulation) pilot is on and average charging power less than a certain limit (2.7 kW).
Mode 3 charge	PWM (Pulse Width Modulation) pilot is on and average charging power more than a certain limit (2.7 kW).
Rapid charge	“Quick Charging” status is on.
Vehicle-to-Grid	“Quick Charging” status is on but energy coming out from the battery is more than a certain threshold (0.05 kWh).

The data from the Nissan Leaf used by the property owners was collected from September 2016 to March 2017 and was filtered to extract only the information relating to the events starting and/ or ending at the property. The availability of the EV at the property is shown in Figure 5, which indicates a high availability percentage of the days assessed, with the mid-day usage being largest during the afternoon school pick-up between 2pm and 4.30pm.

3.1.1 Charge/ Discharge Simulation

The charge and discharge cycle for the vehicle is calculated from the net electricity demand of the property, and through a ranking system, indicates which net building demand events require V2G operation. For each

day evaluated, initially the total charging requirement based on the journey information is calculated to establish the minimum demand value. Vehicle location data is used to populate the availability of the vehicle with a 0 or 1 ranking depending on if the vehicle is present or away from the property. Based on the net demand/ supply values, the charging/ discharging cycle is ranked by largest net demand to smallest, and largest net generation from largest to smallest. Where the vehicle is available, a power rating is assigned for each 5-minute time step until the charge/ discharge target values for the day have been reached. These values are set based on the maximum battery capacity of the vehicle, the minimum discharge SoC value, the driving demand requirements and time availability. Finally, the electricity tariff is taken into consideration, with the EV only able to charge during the off-peak electricity tariff unless all of the power demand can be met by the PV generation.

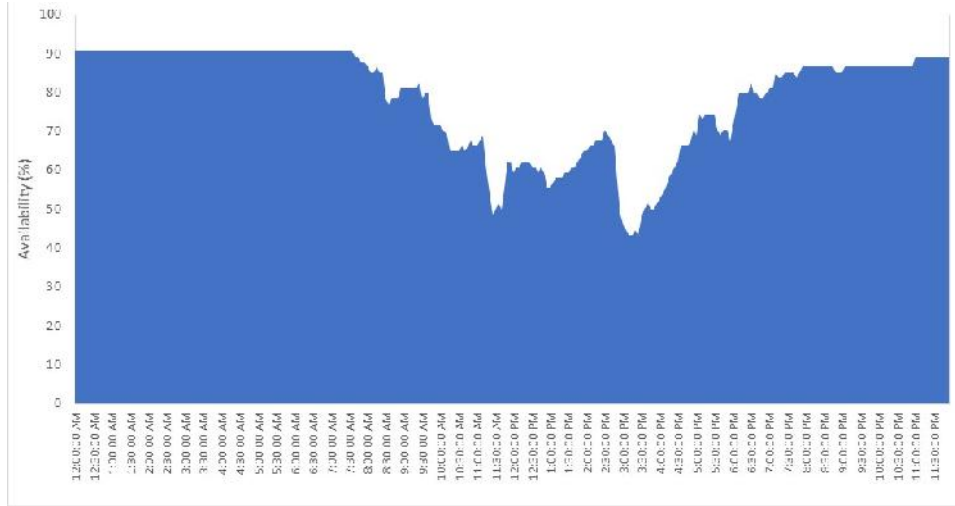


Figure 5: EV availability profile for V2G services

3.3 Calculating Cost Savings Due to Vehicle-to-Grid

The daily benefit to the home owner in utilising V2G to offset a proportion of grid-imported electricity (Bld_s) is a function of the original electricity cost (Bld_c) (£), the energy supplied per day by all vehicles simulated (AE_s), the V2G service tariff payment and the infrastructure costs of the V2G technology equated to a daily value (I_c), specified as a variable [19].

$$B_s = B_c - (B_c - (V2G_T \times A_s) - I_c) \quad (1) [19]$$

The cost savings as a result of the V2G intervention builds upon the work previously specified by Uddin et al. [22], which quantified the cost saving experienced as a result of battery storage intervention. This specified the cost savings as a result of the battery storage operation are calculated based on the total energy imported with and without the battery and the export Feed-In Tariff paid to the homeowner for PV export. $\Delta E(k\ h)$ is the reduction in grid imported electricity due to integrating PV with the battery storage system (assumed here to be the EV with V2G unit) and is given by:

$$\Delta E = E_{-b} - E_{+b} \quad (2) [22]$$

where E_{-b} is the electricity exported without battery storage and E_{+b} is the electricity exported with battery storage. The income paid for energy export without battery storage (G_{-b}^e [£]) is a product of E_{-b} and the export tariff C^e [£/kWh]:

$$G_{-b}^e (\text{£}) = E_{-b} \times C^e \quad (3) [22]$$

while the export income with battery storage (G_{+b}^e [£]) is given by:

$$G_{+b}^e (\text{£}) = E_{+b} \times C^e \quad (4) [22]$$

The cost savings as a result of battery storage $S(\text{£})$ is therefore:

$$S = \Delta E \times C^{ii} - (G_{-b}^e - G_{+b}^e) = \Delta E (C^{ii} - C^e) \quad (5) [22]$$

where C^{ii} [$\text{£}/\text{kWh}$] is the electricity import price.

The variables used within the analysis are given in Table 4.

Table 4: Variable set values for case study analysis.

Variable	Value	Unit
Battery discharge limit		%
Vehicle battery capacity	24	kWh
Peak electricity tariff period	08:00 – 01:00	Time
Off-peak electricity tariff period	01:00 – 08:00	Time
Peak electricity tariff price	16.64	p/ kWh
Off-peak electricity tariff price	5.73	p/ kWh
Electricity standing charge	90.41	£/year
V2G unit cost	500	£
Hardware lifetime	8	Years
Hardware installation cost	350	£
V2G unit converter size	3	kW
Static battery size	2	kWh
Static battery converter size	400	W
Static battery price	2000	£
PV generation tariff	13.39	p/ kWh
PV export tariff	4.85	p/ kWh
EV and static battery efficiency	85	%

4 Techno-Economic Benefit of Vehicle-to-Grid Integration

4.1 Vehicle-to-Grid Operation

The technical operation of the vehicle with the V2G unit is simulated for a typical mid-week day from the data analysis period and overlaid onto the daily profile for the building demand. Two operational models are evaluated; fixed rate and variable rate converter. Figure 6 indicates the availability of the vehicle for charging and discharging services on 20/09/2016, along with the building demand and PV generation, as previously shown in Figure 2. This shows that a large portion of the PV generation cannot be used to charge the EV as it is not available, however the majority of the building demand can be delivered by the vehicle. The vehicle is available over the night time for either charging or discharging services, depending upon the battery SoC throughout the day.

For the day analysed here, the energy consumed for driving was 3.09kWh, which is fairly typical for the mid-week usage of vehicle. This leaves 9.22kWh available for V2G services and it is assumed that the vehicle will be fully charged by the time the first journey is required to be driven at 11:10am.

For the fixed rate scenario, a charge/ discharge cycle has therefore been implemented, as shown in Figure 7, which is optimised to harness the maximum available PV generation and the electricity pricing profile of the property for charging of the vehicle and discharge when the building demand is highest.



Figure 6: Indication of vehicle availability for V2G services for typical weekday overlaid onto stacked bar chart of property demand and PV generation profile. Also shown is the maximum charge/ discharge converter rates for the V2G unit.

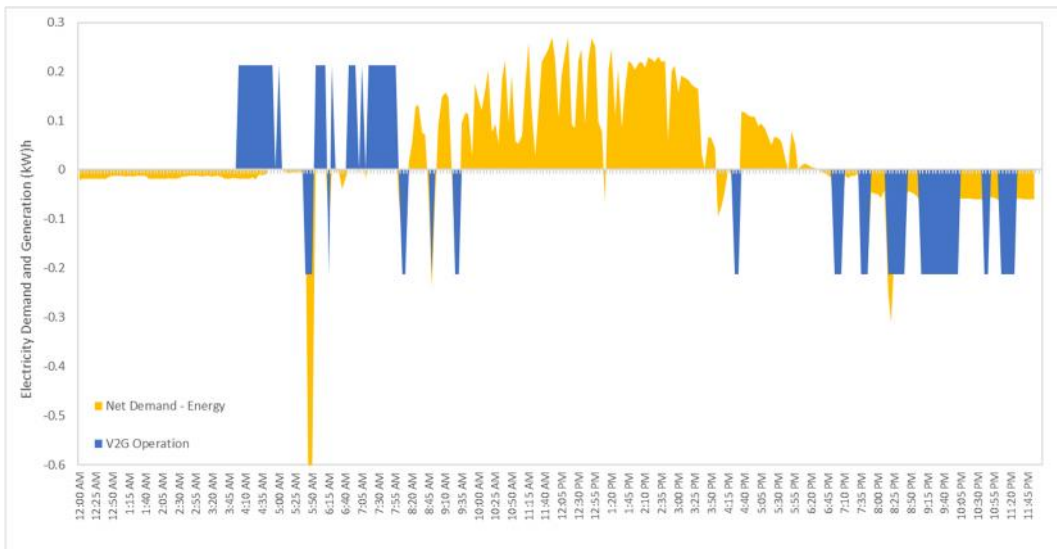


Figure 7: V2G operation with generation and demand profile for property.

To avoid the loss of energy when the EV is discharged due to the fixed rate converter, the V2G operation has been simulated with a variable rate converter, as seen in Figure 8. Here, the EV still charges during the off-peak electricity tariff, but it can also charge from the solar at a variable rate, meaning a larger portion of the solar generation is utilised. Discharging also occurs in line with the demand profile, meaning large amounts of energy are not lost from the EV battery when discharging to support the property.

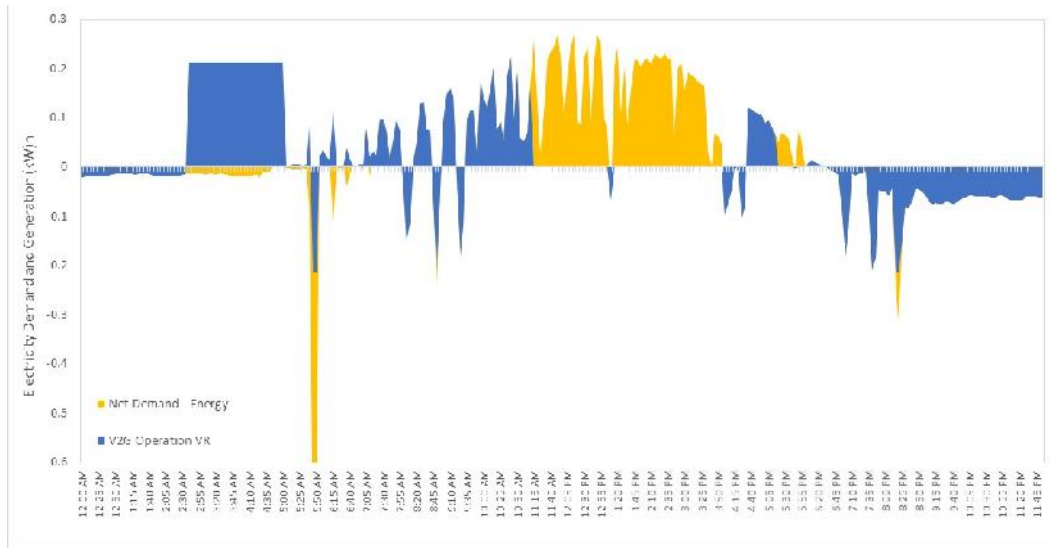


Figure 8: V2G operation with a variable rate converter and property net energy demand for a typical day in July. The EV charges during the cheap night time economy 7 tariff and discharges to match the demand when solar cannot support it.

4.2 Cost Savings from Vehicle-to-Grid Operation

Using equations 1-5, the economic savings as a result of the fixed rate converter V2G operation shown in Figure 7 is £0.26 per day, which is equal to £95 per annum based on the fixed rate converter modelled. Including the hardware costs, this saving is reduced to £18 for the V2G unit. However, a case can be made that the hardware cost is negligible as it would already be required to charge the vehicle. Compared with the existing battery operation, which provides a saving of -£0.20 per day, the V2G unit operational model described here indicates a better operational model, but only by around £30 per annum. The savings from the battery operation including the hardware costs is £1 per annum, which indicates the V2G unit and EV operation, whilst the larger rate converter is not fully utilised, still represents a greater saving to the homeowner than the static storage system.

The EV charging operation shown in Figure 7 has been simulated to function in the same way as the static battery, charging when there is an excess of solar generation. The EV discharges when there is an excess of demand within the property as opposed to the static battery, which discharges at the same period every day. With the static battery operation, it is evident that a larger battery could be installed to support the house, however the cost to saving ratio would have to be greater than the current EV with V2G unit in order for a benefit to be received. Based on the V2G operation simulated here, due to the large fixed rate converter, just over 3kWh are estimated to be lost each day and exported back out to the grid. This equates to roughly £200 per annum of wasted income that could otherwise be utilised by the property if properly managed.

However, operating the EV battery as a variable rate converter could save around £320 per annum, or around £200 including the cost of the V2G unit. Again, it could be argued that the unit and installation cost are irrelevant as they would be needed regardless of whether V2G operations were being performed. Operating the EV in this way maximises the PV usage, increasing the usable percentage to 38%, which would be increased further if the vehicle were at the property during the peak PV generation period.

5 Conclusions

A typical UK domestic property was used as a case study, which has PV and a small battery installed. This paper has explored the ability for an EV connected to a V2G unit to reduce the grid demand of the property in combination with the PV and the real-world operation of the battery storage unit has been compared with

a simulated operation of a fixed and variable rate V2G unit converter. The results indicate that the current battery storage system installed in the property does not effectively utilise the excess PV generation, resulting in an annual saving of £1, meaning the system costs are never paid back.

A 3kW V2G unit was simulated to operate using the same operational parameters as the existing battery storage unit and produced a saving of £18 per annum including the hardware costs, which is a 10-year payback period. The fixed rate converter of 3kW for the V2G unit meant a large amount of the discharged energy was lost, over 1,000kWh per annum. The variable rate converter simulated could produce an annual saving of £200 for the homeowner including the hardware costs and resulted in 12% extra utilisation of the PV generation, which was only exported when the EV was not present at the property. Overall, results indicate that a V2G unit with a variable rate converter could provide a significant cost saving to homeowners with EVs or prospective EV owners.

6 Acknowledgments

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