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Exploring Opportunities for Vehicle-to-Grid Implementation through Demonstration Projects

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Abstract: Global warming, pollution, and increasing energy demand have compelled electrification of the transport sector. Electric vehicles are not only an attractive and cleaner mode of transport, but they also possess the capacity to offer flexible storage alternative based on bidirectional vehicle-to-grid schemes. Vehicle-to-grid or V2G technology permits electric vehicles' batteries to store energy and discharge it back to the power grid during peak-load periods. However, the feasibility and economic viability of V2G is still a matter of concern and needs investigation. In this paper, the authors delved into the feasibility of V2G technology by analysing the real time-charging data of a V2G demonstration project named EV-elocity, located at the University of Nottingham campus in the UK. The authors analysed the charging data and trip-status data of two charging sites and put forward some insights regarding the feasibility of V2G and the behavioural traits of the vehicles. This paper will enlighten the research community regarding the feasibility and benefits of V2G in a real-world environment by analysing the charging/discharging and vehicle behaviour and reporting the opportunities and benefits of vehicle-to-grid technology.

Keywords: electric vehicles; EVs; bidirectional charging; vehicle-to-grid; V2G; vehicle-to-everything; V2X; vehicle-to-building; V2B; EV-elocity

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1. Introduction

Electrification of the transport sector is one of the major steps towards achieving net-zero targets [1]. The UK government has declared the allocation of 350 million pounds to support the electrification of vehicles [2]. Electric Vehicles (EVs), apart from being a cleaner mode of transport, have the capability of offering storage alternative and supplying power back to the grid during peak-load periods by bidirectional vehicle-to-grid (V2G) technology. V2G enables energy to be pushed back to the power grid from the batteries of EVs [3]. EVs have the capacity to serve as a flexibility resource and provide power to the grid during peak-load periods. Further, using smart-coordinated charging instead of dumb charging can solve problems such as voltage instability, degradation of reliability indices, and harmonics without compromising the safety and security of the power grid [4,5]. EVs can be charged when the load demand is low and renewable generation is high in order to optimise the cost of charging and reduce carbon emissions [6]. Also, EVs can store the excess renewable generated when power demand is low. Thus, V2G can enable a reduction in the reliance on fossil fuels and relieve the grid during emergencies [7].

Recently, a considerable amount of research work has focussed on analysing different aspects of V2G such as the feasibility, architecture required for V2G, framework for V2G, scheduling, and economic benefits of V2G. For example, Wei et al. [8] explored the planning of an integrated-energy system having V2G as a flexible storage medium. Elliott et al. [9] investigated the environmental impacts of a V2G-enabled school bus fleet with a DC fast charger. Li et al. [10] proposed a scheduling strategy for V2G that took into account drivers' willingness. Shipman et al. [11] predicted the capacity of V2G by a deep recurrent neural network. Shipman et al. [12] predicted the possible vehicle locations for successful implementation of V2G schemes. Liu et al. [13] put forwarded a distributed-economic-dispatch strategy incorporating V2G during peak-load periods. Attou et al. [14] analysed enhanced valley-filling and peak-shaving strategies of power systems incorporating V2G. Hassija et al. [15] proposed a blockchain-based framework for energy trading in a V2G network. Li et al. [16] optimised the two-directional behaviours of V2G, taking into account the battery health. Sufyan et al. [17] presented charge-coordination- and battery-lifecycle analysis after the incorporation of V2G. Bibak et al. [18] analysed how V2G will affect the power-system operating parameters. Wang et al. [19] proposed a blockchain-based rewards scheme for V2G networks. Shipman et al. [20] predicted the capacity of V2G services during the pandemic by a machine learning-based approach. Bui et al. [21] studied the strategies of using a V2G scheme to reduce battery degradation. Waldron et al. [22] put forward how V2G can play a significant role in decarbonising the grid by reducing carbon intensity.

In this work, we investigated the feasibility of a V2G strategy through the analysis of real-world historical charging and trip datasets for two demonstrators installed at the University of Nottingham (UoN). This research focuses on the possibility of V2G by analysing the real time-charging data and trip data of the EV-elocity demonstration project at the University of Nottingham (UoN) campus. The contribution of this work lies in streamlining the feasibility and benefits of a V2G scheme in real time. Thus, this work will enlighten the research community with the real-world analysis of a V2G scheme in terms of feasibility and benefits. The key contributions of this work are as follows:

- Detailed analysis of the charging/discharging and trip dataset of the V2G trial at the UoN campus;
- Analysis of the travel pattern of the vehicles monitored during the V2G trial;
- Analysis of the opportunities of bidirectional V2G and quantification of the benefits; Estimation of the carbon savings achieved by V2G.

2. Overview of Bidirectional Charging

Bidirectional charging enables EVs to act as a demand response medium to give back unused power. EV batteries can export electricity back to the system in different ways, which is called vehicle-to-everything (V2X) [23–25]. More specifically, there are various ways for EV batteries to be used as a source to store and share energy:

- Vehicle-to-building (V2B) or vehicle-to-home (V2H) refers to the concept of using the EV batteries to supply electricity to buildings/homes or to absorb surplus power from buildings when the energy generation exceeds the energy demand [23,26].
- Vehicle-to-grid (V2G) refers to the process of charging and discharging EV batteries through the grid [22–25]. V2G is a technology that allows energy to be returned to the power grid. The EV battery can be charged or discharged depending upon energy production and consumption [27].

V2G technology was first proposed by the research group of Professor Kempton at the University of Delaware [28]. An overview of the architecture of V2G technology is as shown in Figure 1. For successful implementation of V2G technology, the following three conditions must be fulfilled: [28–31]:

1. Power connection for electrical energy flow
2. Control Architecture
3. V2G-compatible EV and charger

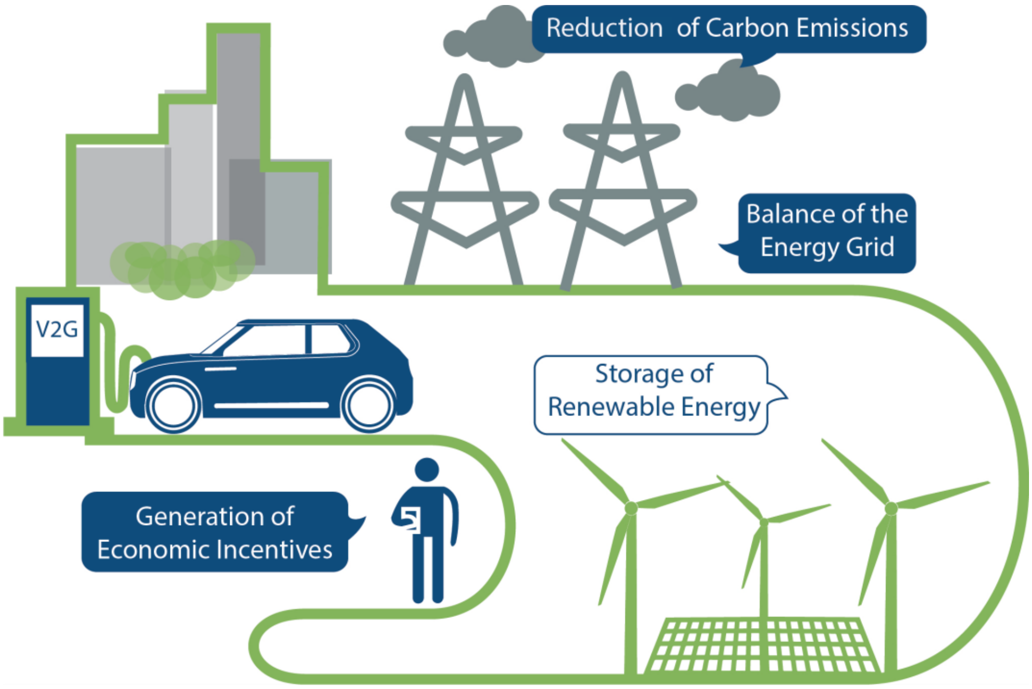


Figure 1. Overview of the V2G architecture.

V2G is a technology that can support some of the most challenging problems of society, such as the reduction of carbon emission from the transport and energy sectors. Nevertheless, this technology has some technical, social, and cultural as well as industrial challenges associated with it. Therefore, the possible benefits and challenges are shown in Figure 2:

Benefits of V2G	Challenges of V2G
◦ Extra power for peak load demand	◦ Lack of scientific consensus
◦ Regulation of the energy system	◦ Battery performance and degradation
◦ Storage of renewables	◦ Eavesdropping
◦ Providing flexibility, reliability and stability to the grid	◦ Tampering with communication messages
◦ Expansion of the energy storage capacity	◦ Denial of service
◦ Optimising the energy and charging costs	◦ Impersonation
◦ Economic incentives for the end users	◦ Cost of technology (EVs & chargers)
◦ Absorbing the surplus energy of the grid providing fast response storage	◦ Anxiety about the challenges presented by implementing V2G
◦ Reducing system costs	◦ Range anxiety
◦ Reduction of greenhouse gas emissions	◦ Data analysis of user behaviour and travel patterns to optimise charging and discharging
	◦ Accesibility of the technology to all users

Figure 2. Benefits and Challenges of V2G [32,33].

3. Demonstration Projects

Several V2X demonstration projects have been executed throughout the world. The V2G Hub [34] compiles a list of 131 vehicle-to-grid projects delivered globally since 2009. The services tested in the projects are frequency response, arbitrage, time shifting, emergency backup, distribution services, and reserves. The V2G demonstrators are mainly located in Great Britain (28 projects), United States (21 projects), Netherlands (17 projects) and Denmark (11 projects), and other countries include Japan, China, Spain, and Italy.

EV-Elocity Demonstration Project

EV-elocity was a research and development project funded by the Office for Zero Emission Vehicles and the Department for Business Energy and Industrial Strategy from the UK government that was facilitated by Innovate UK [35]. This project started in September 2018 and continued up to January 2022 [35]. The project focussed on demonstrating V2G in a range of real-world situations to gain technical, customer, and commercial insights into this technology [35]. The different objectives of the project are as shown in Figure 3. The project was executed by a consortium consisting of organisations such as Cenex, CrowdCharge, Leeds City Council, Nottingham City Council, University of Nottingham, and WMG University of Warwick.

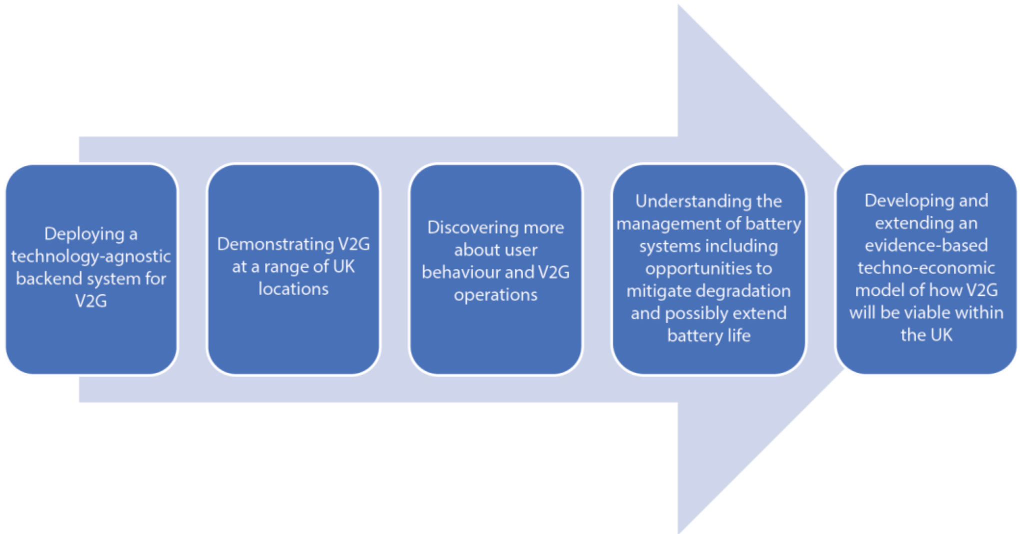


Figure 3. Objectives of EV-elocity project [35].

Two sites managed by the University of Nottingham were considered for this paper. The University of Nottingham has eight campuses, two of which are located overseas. The University Park campus in Nottingham is a living test site for a number of research projects concerned with the reduction of carbon emissions. This campus has the existing V2G charging infrastructure and accessible vehicle behaviour historical data [35]. The description of the two sites is shown in Table 1. The first charger is located at Creative Energy Homes, which is a housing development at the University Park campus. This site has low-energy homes, renewables, micro-grids, energy storage, demand-side management, and other strategies to reduce CO_2 emissions [32]. There is a Nichicon V2G single-phase 7 kW bidirectional charger installed outside this housing [35]. The vehicle connecting to this charger was a Mitsubishi Outlander owned by a UoN staff member. The second site is the Hallward Library building, a relatively old and iconic building inaugurated in 1972 at the University Park campus [35]. It operates from 8:00 a.m. to 9:00 p.m. most of the time, maintaining a high demand for energy for at least 13 h every day [35]. The vehicle connecting to this charger was a Nissan e-NV200 from the UoN fleet. This vehicle was used 24/7 depending on the fleet demand [35]. Both chargers were controlled by an app developed by CrowdCharge.

Table 1. Details of the demonstrators at University of Nottingham [35].

UoN V2G Sites	Type of Vehicles	Type of Chargers
Creative Energy Homes (CEH)	1 Mitsubishi Outlander PHEV, Battery: 13.8 kW	1 × Nichicon 7 kW V2G, ground mounted
Hallward Library	1 Nissan eNV200, Battery 40 kW	1 × Nichicon 7 kW V2G, ground mounted

The project was divided into four phases (Table 2) aiming to deliver the operational strategy as explained below:

- Phase 1—Baselining and Installation: The aim of this phase was to install and test the operation of the V2G chargers and provide the instructions to the end users. This phase did not include data collection as it was designed for testing the operability of each of the chargers.
- Phase 2—Fixed Scheduling Tariff and Carbon Optimisation: The aim of this phase was to optimise the tariff (phase 2a) and carbon emissions (phase 2b) when charging and discharging the vehicles using a fixed schedule. To determine the fixed charging/discharging schedules three variables were considered: vehicle utilisation, electricity tariff, and grid carbon intensity. For the tariff optimisation (phase 2a), two schedules were designed for each demonstrator. For the carbon optimisation (phase 2b) one schedule was designed for all the demonstrators based on historical data of the grid carbon intensity.
- Phase 3—Dynamic Scheduling Tariff and Carbon Optimisation: The aim of this phase was to optimise the tariff (phase 3a) and carbon emissions (phase 3b) when charging and discharging the vehicles using the CrowdCharge app that requested from users the estimated time to plug-in and to plug-out the vehicle, and the desired final state-of-charge (SOC) of the battery. This app was intelligently optimising the charging/discharging in terms of costs and carbon emissions without compromising user operation of the vehicle. Users were entitled to override the schedules and immediately charge the vehicles if required.
- Phase 4—Battery Conditioning: The aim of this phase was to charge and discharge the vehicle while optimising the battery health. The parameters used for this charging profile were designed by Bui, T.M., et al. [21] based on their research to reduce the battery degradation of electric vehicles using vehicle-to-grid systems. In this schedule, users were asked to register the plug-in time, plug-out time, and the percentage state-of-charge desired at the end of the V2G session. Then the charger took the state of charge to 50%, holding at this level for as long as possible before taking the state of charge to the required percentage at the plug-out time.

Table 2. Timeline of different trial phases [35].

Phase	Description	Time of Data Collection
1	Installing and testing chargers	4 January 2021–30 April 2021
2a	Fixed scheduling tariff optimisation	3 May 2021–20 June 2021
2b	Fixed scheduling carbon optimisation	21 June 2021–1 August 2021
3a	Dynamic scheduling tariff optimisation	2 August 2021–19 September 2021
3b	Dynamic scheduling carbon optimisation	20 September 2021–31 October 2021
4	Conditioning battery health	1 November 2021–31 January 2022

In Figure 4, the stages of data collection (phases 2–4) are illustrated with each of the sub-stages. For phase 2, data shown are the charging and discharging times of the vehicles at Creative Energy Homes and Hallward Library. For instance, in the case of the Tariff Optimisation Schedule (2a) at CEH the vehicle would charge between 7:30 a.m. and 1:30 p.m., discharge from 3:00 p.m. to 6:30 p.m., and charge between 6:30 p.m. and 9:00 p.m. These schedules were designed according to the vehicle patterns of usage and the electricity tariff per hour. In phase 2b, the charging schedule was adjusted to charge overnight and at midday, and to discharge at 6:00 a.m. and 7:30 p.m. to optimise carbon costs. Phase 3 consisted of Dynamic Scheduling; in Figure 4 is presented a screenshot from the CrowdCharge app with an example of the weekly schedule plan editable by users. In the weekly journeys, users were registering their plug-in time, the plug-out time, and the miles required per day when unplugging the vehicle. Phase 4 was similar to phase 3 regarding the information required by the app; the difference was about how the charger was charging/discharging the vehicle according to the plug-in time available and setting up some requirements to optimise the battery ageing.

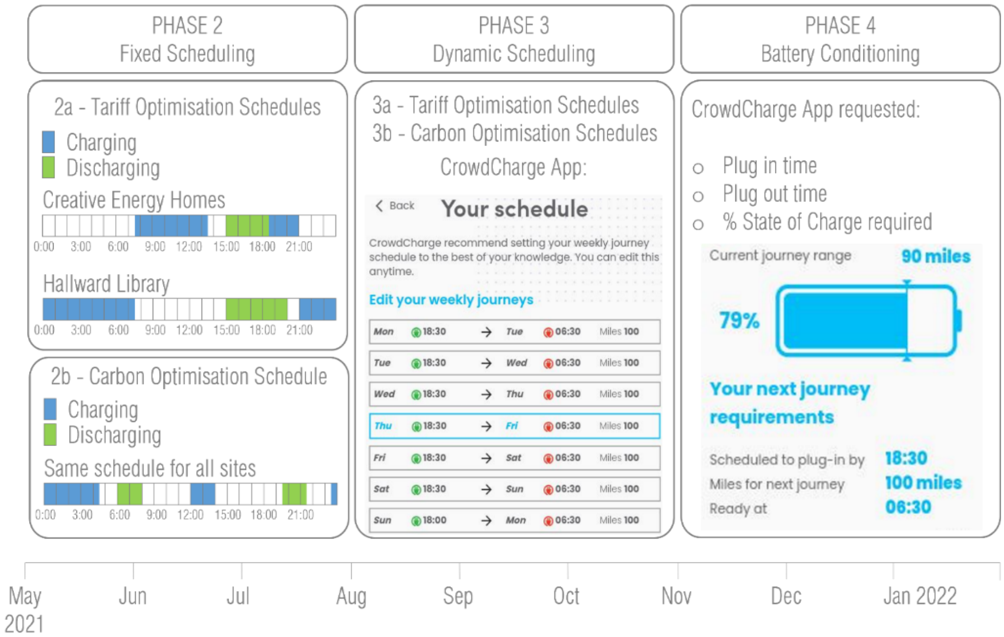


Figure 4. Different trial phases of EV-elocity project [35]. This figure only includes the phases of data collection; Phase 1 is not included as it was the time allocated for installing and testing the chargers.

4. Methodology

4.1. Description of Datasets

Three datasets were analysed in this work. The first dataset was the charging data collected at Creative Energy Homes, the second one was the charging data collected at Hallward Library, and the third one is the trip data of the Nissan eNV200.

The charging dataset of Creative Energy Homes consists of 53 events recorded over the time span from 6 March 2021 to 13 December 2021. The events recorded are not continuous in nature because the vehicle was also charging at other locations. The dataset contains information related to each charging and discharging event: event ID, date and time of the event, start and end state of charge (SOC), peak import and export power, charging and discharging energy, charging and discharging duration. The charging sessions during 2021 for the Creative Energy Homes location were quite sparse, due to the increase of home working during that year due to COVID-19. There were some dummy events observed in the dataset where neither charging nor discharging took place. The majority of the charging events took place in office time and during weekdays.

The charging dataset for Hallward Library is denser in nature compared to the Creative Energy Homes dataset. A total of 190 events were recorded for this site. This dataset is much denser as compared to Creative Energy Homes dataset as this vehicle was used for patrolling the University campus. The dataset contains information related to start and end SOC, peak import and export power, date and time of the event, session ID, charging and discharging energy, and charging and discharging duration. Some dummy events where no charging or discharging took place were also observed in this dataset.

Further, Table 3 represents the distribution of events over the phases for both Creative Energy Homes as well as Hallward Library. It was observed that for Creative Energy Homes, most events occurred during phase 3b. And it was observed that phase 4 recorded the highest number of discharging events. For Hallward Library, phase 4 registered the highest number of total events as well as discharging events. Phase 3a reports the lowest number of events and only 3 discharging events were reported in this phase.

Table 3. Distribution of the events recorded for Creative Energy Homes and Hallward Library.

Creative Energy Homes			
Phase	**No. of Events**	**No. of Charging Events**	**No. of Discharging Events**
2a	4	4	0
2b	4	4	0
3a	6	6	0
3b	23	23	4
4	12	12	6
Hallward Library			
Phase	**No. of Events**	**No. of Charging Events**	**No. of Discharging Events**
2a	43	40	9
2b	25	25	23
3a	17	17	3
3b	51	51	18
4	54	53	37

The trip dataset contains 2116 trips of the V2G-enabled vehicle of Hallward Library after filtering between May 2021 and December 2021. The dataset contains information about time of trips, distance of trips, driving time, idle time, energy consumed, state of charge, and type of trips. The distribution of the trips over the phases is as shown in Table 4. The highest number of trips was recorded in phase 3b.

Table 4. Distribution of vehicle trips over the phases (data from the Nissan eNV200).

Phase	Number of Recorded Trips
2a	585
2b	388
3a	275
3b	619
4	249

The trip data of the Nissan eNV200 consisted of the number of journeys made by the vehicle during the research. Table 4 summarises the number of trips per phase; the busiest phase for the vehicle was phase 3b (20 September to 31 October), which corresponds to the busiest period of the year on campus due to the start of the academic year.

4.2. Method and Assumptions

In this work, the raw real-time-historic data of the V2G trials at UoN campus were analysed. The analysis was performed in three stages. In stage I, the charging data of the two demonstration sites of UoN campus was analysed. In stage II, the vehicle behaviour was analysed. In stage III, the opportunities and benefits of bidirectional charging were quantified based on the results of stage I and stage II. The methodology and data analysed during the three stages is as shown in Figure 5. A description of the aforementioned stages is as follows:

- Stage I: Charging and discharging data registered by the chargers at Creative Energy Homes (stage Ia) and Hallward Library (stage Ib) were analysed. At first, the datasets were filtered, and incomplete events, if any, were removed. Then, parameters such as start and end SOC, peak power import and export, charging and discharging energy, charging and discharging duration, and the monthly and seasonal distribution of events were quantitatively analysed.
- Stage II: Trip data relating to the vehicle monitored at the Hallward Library site was filtered and analysed. The parameters such as driven and idle times, SOC at the

start and end of trip, travelled distance, type of trip, and energy consumed were quantitatively analysed from the filtered dataset.

- Stage III: This was concerned with quantifying the opportunities and benefits of V2G, based on the results of stage I and stage II. In this stage, these included the probability of V2G possible events, likelihood of vehicle being plugged in, likelihood of trip start time, standing time between two consecutive trips, distance between vehicle standby location and the nearest charger, likelihood of charger at a distance of 100 m or 500 m when the vehicle is in standby mode, probability of V2G possible events coinciding with peak-load times of typical UK load curve, capacity of V2G to flatten the load curve, and carbon savings from V2G. The probability of possible V2G events was calculated based on the assumption that discharging would be allowed only when the start SOC was more than 50%. Even though the dataset contained discharging events as well, this probability was calculated in order to check whether the discharging capacity of the vehicle was fully explored or not. Likelihood of vehicle being plugged in at a particular time was computed by dividing the frequency of the vehicle being plugged in at that time divided by the total number of events. Likelihood of trip start times was computed by dividing the frequency of a trip starting at a particular time by the total number of trips. Distance between vehicle standby location and nearest charger was computed by Haversine formulae, as described by Shipman et al. [12]. The load flattening and carbon savings from V2G were calculated for the UK household case. The computation included the household-electricity-load curve as a reference, the power exported from an electric vehicle (reference taken from peak power import/export registered in the V2G real-world trials), and a V2G scheme based on supporting homes at peak hours by discharging electric vehicles.

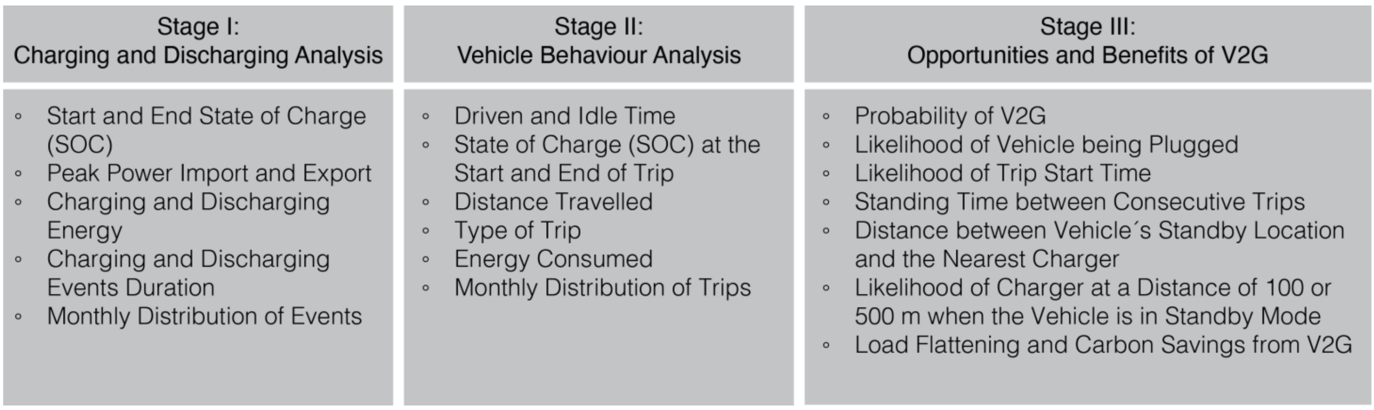
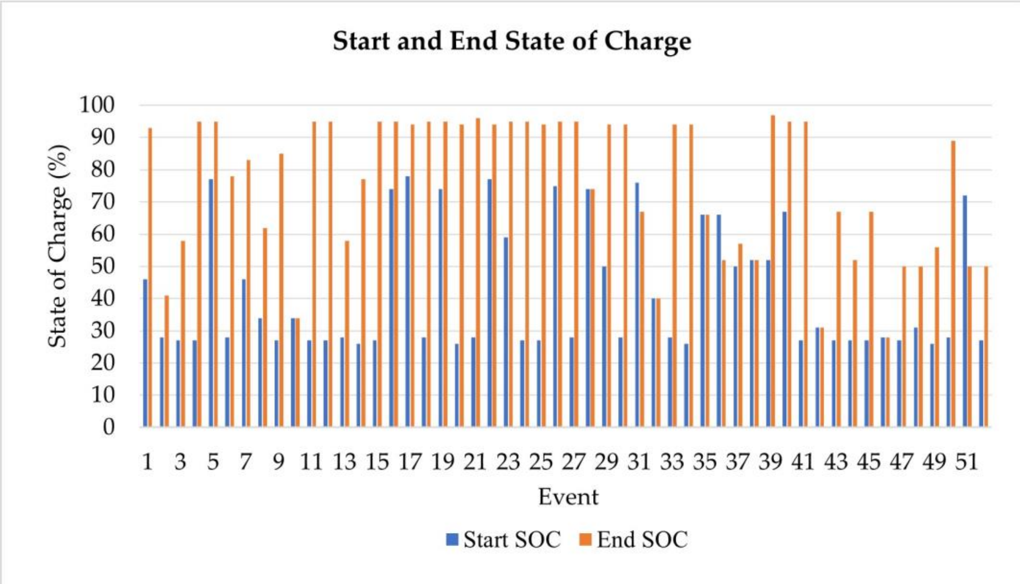


Figure 5. Methodology illustrating the three stages.

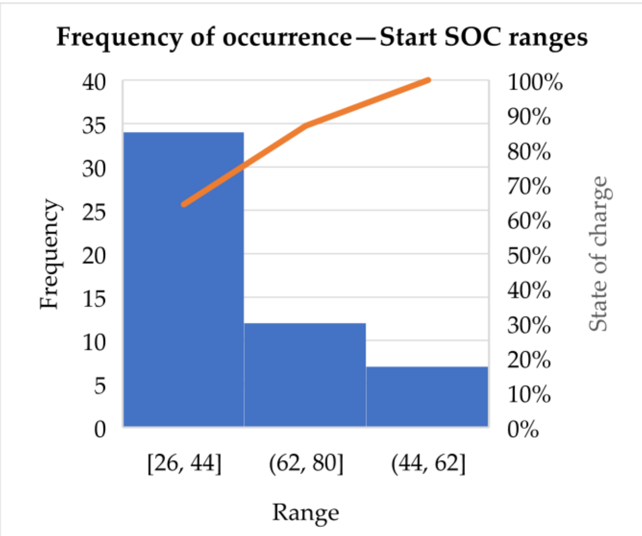
5. Results

5.1. Stage Ia: Charging and Discharging Analysis for the Vehicle Connecting at CEH

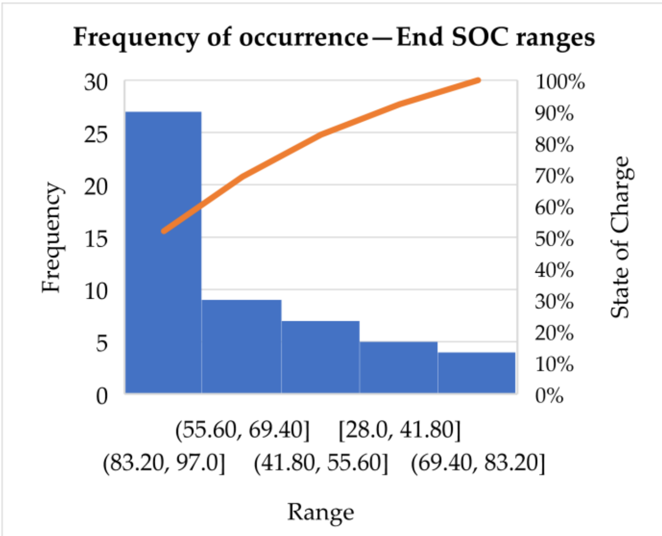
The charging and discharging analyses were performed for the dataset of the charger at CEH by the methodology illustrated in Figure 6. Firstly, the start and end SOC were analysed as represented in Figure 6. Figure 6a shows the variation of start and end SOC for the events at Creative Energy Homes. It was observed that the start SOC of the vehicle varied within the range of 26% to 78%. The end SOC ranges oscillated between 28% to 97%. Further, Figure 6b,c presents the pareto chart representing the frequency of occurrence of different ranges of start and end SOC, respectively. It was observed that the start SOC range of 24–44% obtained the highest frequency, and the end SOC range 83.2–97% obtained the highest frequency.



(**a**) Start and end SOC of the events registered by the charger installed at CEH



(**b**)



(**c**)

Figure 6. Plot of Start and End State of Charge for the events at CEH (**a**) and the pareto charts showing the Frequency of Occurrence of the Start and End SOC at different ranges, with each column representing a range of SOC (**b**,**c**).

Figure 7 represents the variation of peak power import and export for the events of the vehicle connecting at Creative Energy Homes. The peak-power-imported data is a critical element for investigating the impact of EV charging on the power grid operating parameters. It was observed that the highest peak power import was 5.97 kW, and the highest peak power export was 5.80 kW. As the full capacity of the chargers was 7 kW, it was estimated that the maximum power import and export capacities achieved were 85.8% and 82.8%, respectively.

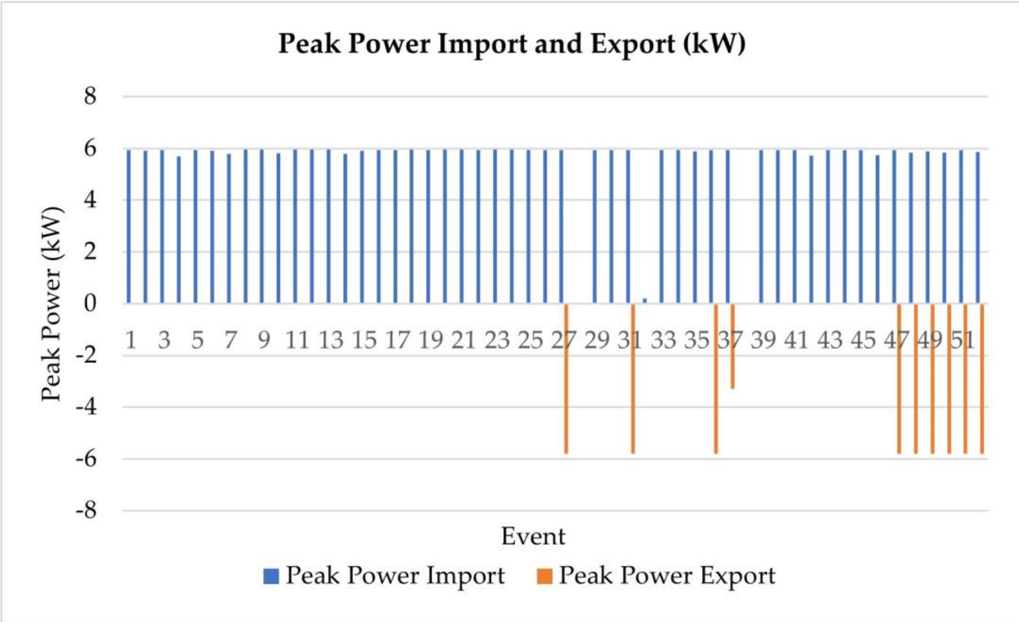


Figure 7. Plot of peak power import and export for the events registered by the charger at Creative Energy Homes.

Table 5 presents the variation of peak power import and export. It was observed that the mean power imported and exported during that time span was 5.5 kW and 5.54 kW, respectively. It must be noted that the average power export was calculated by considering only the events where discharge took place and not the total number of events over the time span. Thus, the average power exported was relatively low as compared to average power imported for this dataset thereby indicating that the V2G capability may not have been fully utilised.

Table 5. Descriptive statistics of peak power import and export for CEH.

Peak Power Import (kW)			Peak Power Export (kW)		
Maximum	**Minimum**	**Mean**	**Maximum**	**Minimum**	**Mean**
5.97	0	5.5	5.80	0	5.5

The charge as well as discharge energy per session for the site were analysed. Figure 8 presents the plot of charging and discharging energy for different events at CEH. The highest charging energy per session reported was 10 kWh and the highest discharge energy reported was 5.4 kWh. The charge and discharge duration were analysed as shown in Figure 9. It was observed that the discharging events duration were relatively low. In some events, both charging and discharging were observed. However, no event where only discharging took place was recorded.

Further, month-wise analysis of the dataset was performed as shown in Figure 10. It was observed that the charging events were relatively low in March, April, May, and June due to increased work from home during the pandemic and summer holidays. And October recorded the highest number of charging events. The events increased during September as this was the first academic year of work from office after the pandemic. However, the number of events again decreased in November and December as COVID-19 cases started to rise and people again started working from home.

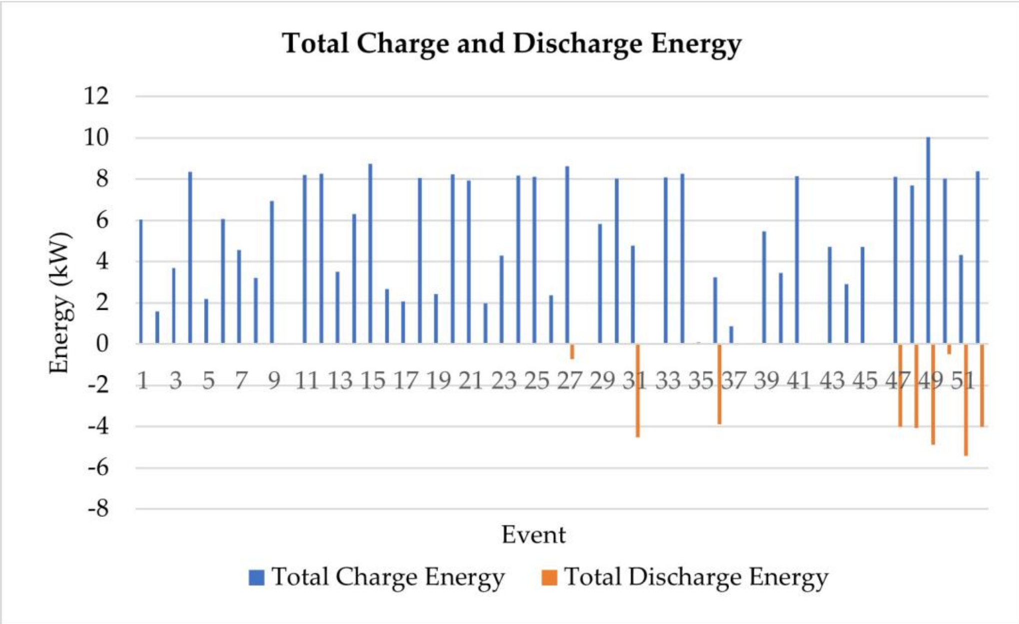


Figure 8. Plot of total charging and discharging energies for Creative Energy Homes.

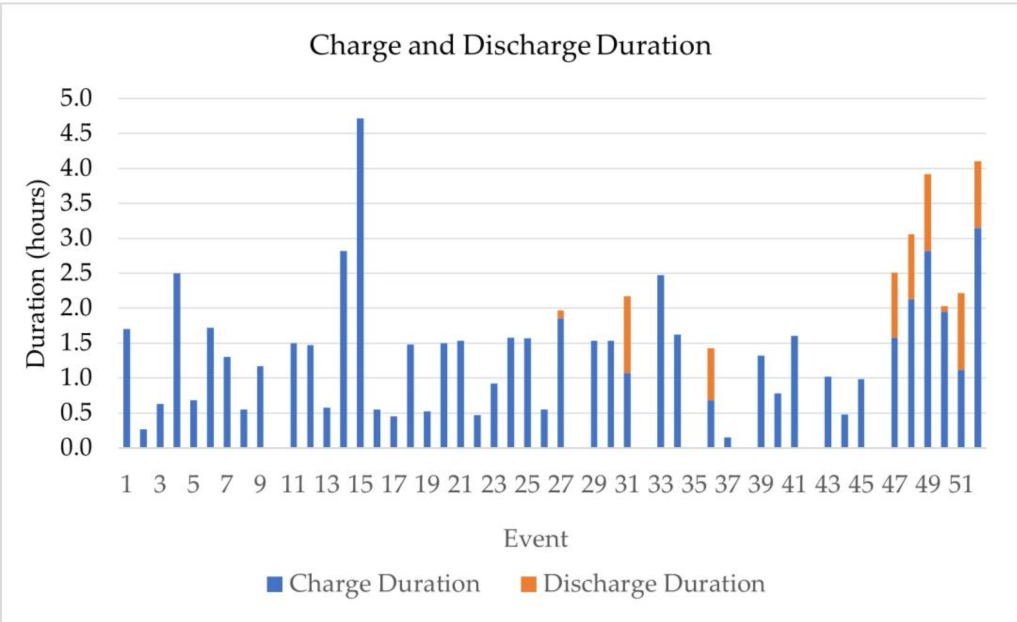


Figure 9. Plot of total charging and discharging durations for Creative Energy Homes.

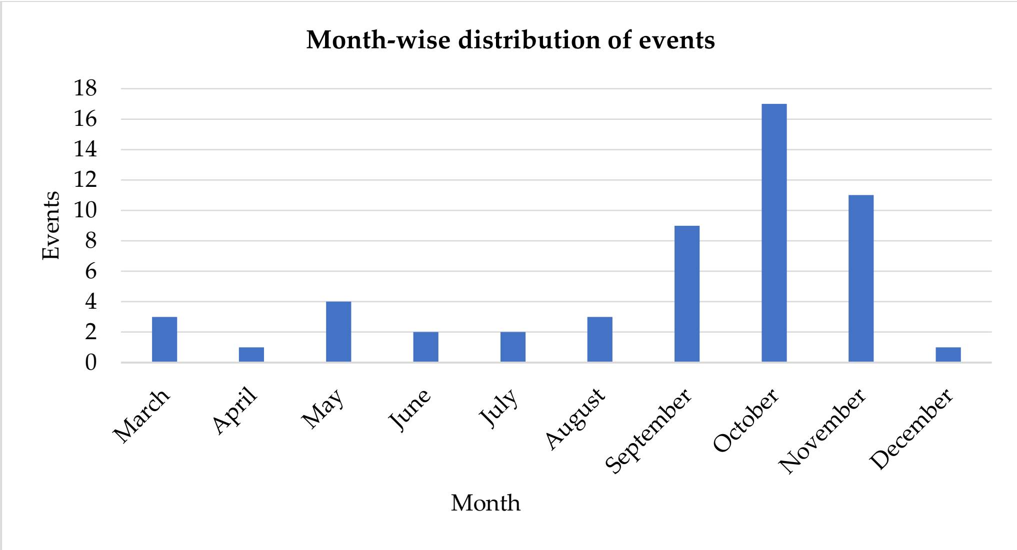


Figure 10. Month-wise distribution of events at Creative Energy Homes.

5.2. Stage Ib: Charging and Discharging Analysis for the Vehicle Connecting at Hallward Library

The charging and discharging analyses were performed for the dataset of Hallward Library after filtering the incomplete events by the methodology explained before (Figure 5). Figure 11 shows a plot of start and end SOC for the recorded events of the vehicle connecting to the V2G charger at Hallward Library. It was observed that the highest start SOC recorded is 91% and the lowest start SOC recorded is 1%. And the highest end SOC reported is 100% and the lowest end SOC reported is 1%. It must be noted that the event for which end SOC of 1% is observed is a discharging event. The lowest SOC were recorded over the latest events (130 to 190), which correspond to stages 3b and 4.

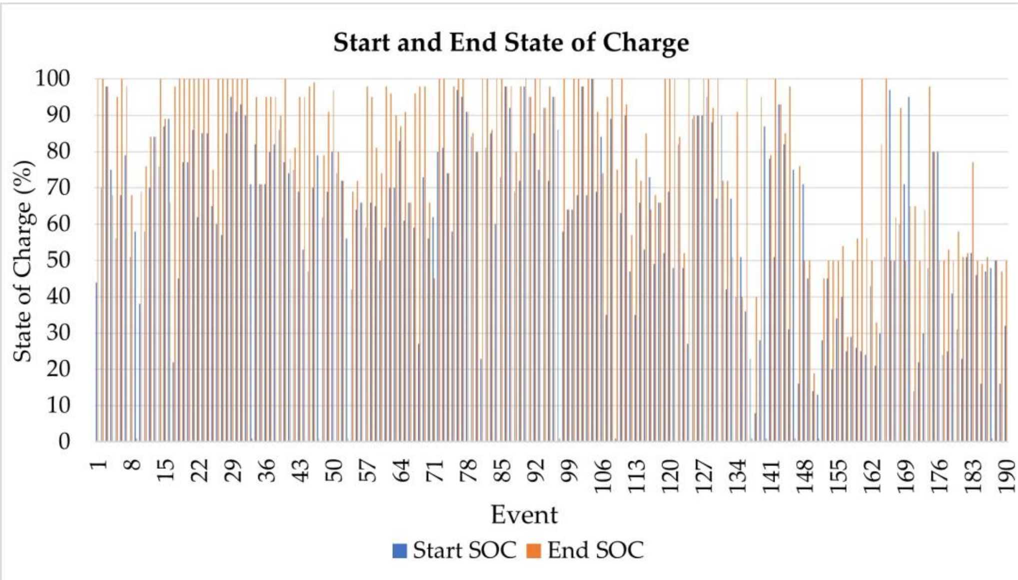


Figure 11. Start and End SOCs of the events registered by the charger installed at Hallward Library.

Figure 12a,b presents the pareto chart representing the frequency of occurrence of different ranges of start and end SOC, respectively. It was observed that the start SOC range of (63–75) % has obtained the highest frequency and the frequency of events with a start SOC below 13% was very low. And the end SOC range of (83.5–100) % has obtained the highest frequency and the end SOC below 34% rarely occurred.

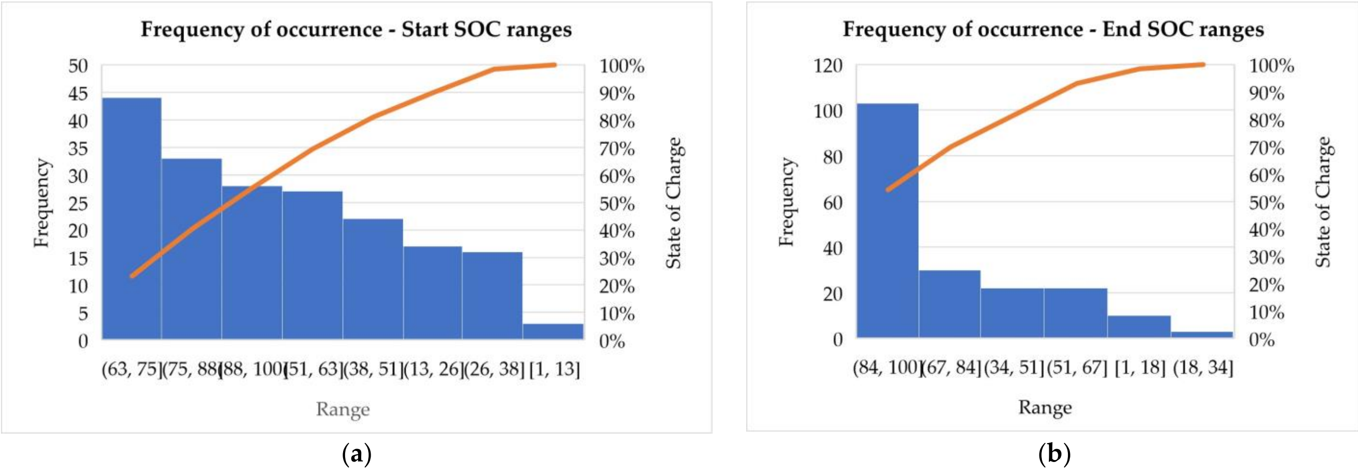


Figure 12. Plot of Start and End States of Charge for the events at Hallward Library. (**a**) Pareto chart showing the frequency of occurrence of different ranges of start SOC at Hallward Library. Each column represents a range of SOC. (**b**) Pareto chart showing the frequency of occurrence of different ranges of end SOC at Hallward Library. Each column represents a range of SOC.

The peak power imported and exported for different events at the Hallward Library site were analysed and the plot of peak import and export power is shown in Figure 13. It was observed that the highest peak power import was 5.94 kW and the highest peak power export was 5.81 kW, representing maximum power import and export capacities of 85% and 83%, respectively.

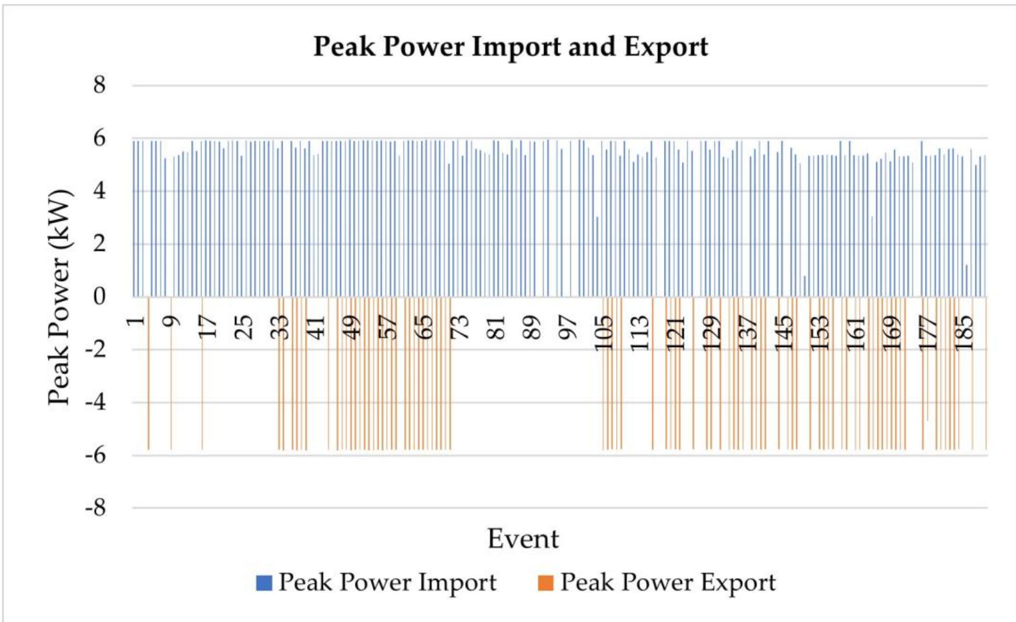


Figure 13. Plot of peak power import and export for the events registered at Hallward Library.

Table 6 reports the maximum, minimum, and mean values for peak power import and export. Mean peak power import was 5.2 kW, and mean peak power export was 5.71 kW (considering only the discharge events). It was observed that the maximum and mean power export were very similar.

Table 6. Descriptive statistics of peak power import and export for Hallward Library.

Peak Power Import (kW)			Peak Power Export (kW)		
Maximum	**Minimum**	**Mean**	**Maximum**	**Minimum**	**Mean**
5.9	0	5.2	5.8	0	5.7

The charging and discharging energies for the site were analysed as shown in Figure 14 by the plot of charging and discharging energies for different events at that site. It was observed that the highest charging energy reported was 122.5 kWh. The highest discharging energy reported was 85.8 kWh, and these high values are explained by the duration of the events as the vehicle was connected for around 40 h.

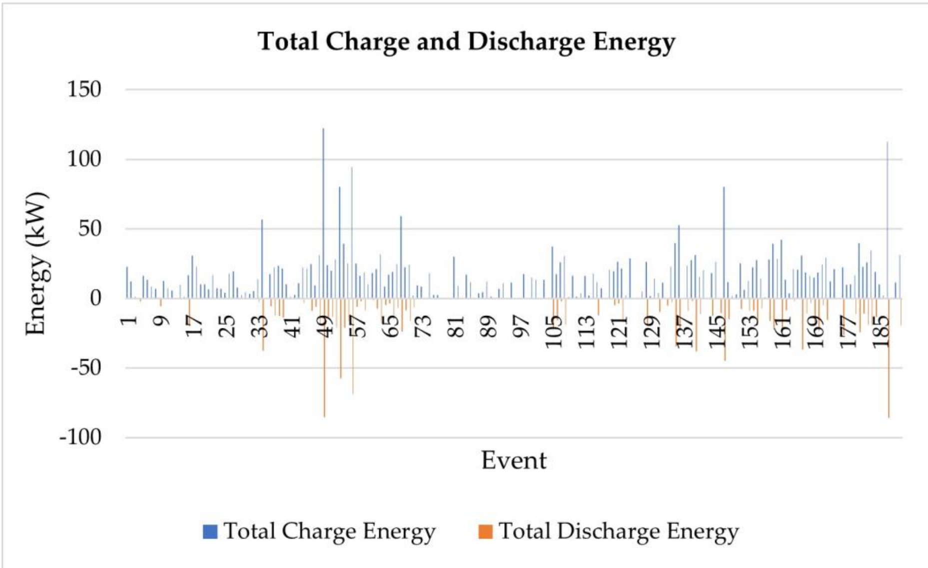


Figure 14. Plot of total charging and discharging energy for the events at Hallward Library.

The charge and discharge duration of the Hallward Library site was analysed as shown in Figure 15. In some events, both charging and discharging were observed. Also, in some events only discharging was observed.

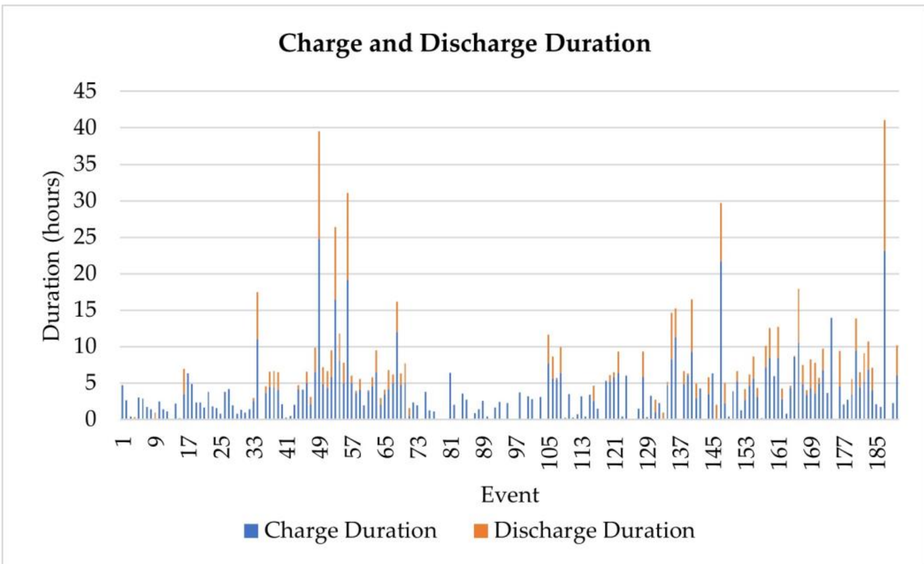


Figure 15. Plot of total charging and discharging durations for the events at Hallward Library.

Further month-wise analysis of the dataset was performed as shown in Figure 16. It was observed that the highest number of events occurred during September, October, and November, which are the busiest months in a university campus in the UK. The number of recorded events was relatively low for August because the vehicle was down for repair from 6 August 2021 to 2 September 2021.

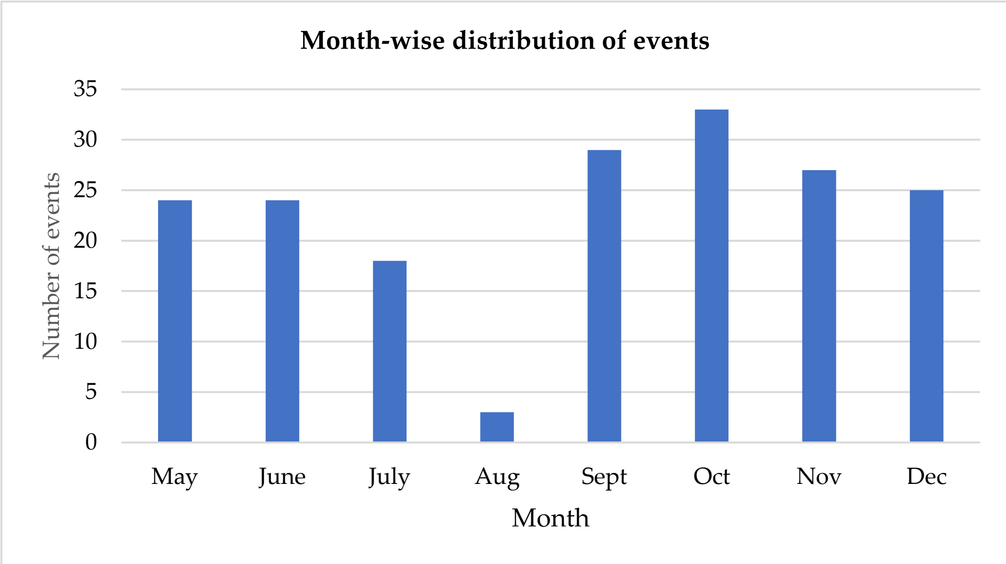


Figure 16. Month-wise variation of the events at Hallward Library.

5.3. Stage II: Vehicle Activities Analysis

The trip data of the vehicle monitored at the Hallward Library site were quantitatively analysed by the methodology depicted in Section 4. Firstly, the driven and idle times of the recorded trips were compared as shown in Figure 17. It was observed that an idle peak of 70,655 corresponds to a stop of over 19 h and a driven peak time below 6000 s, which is equivalent to 1.6 h driving.

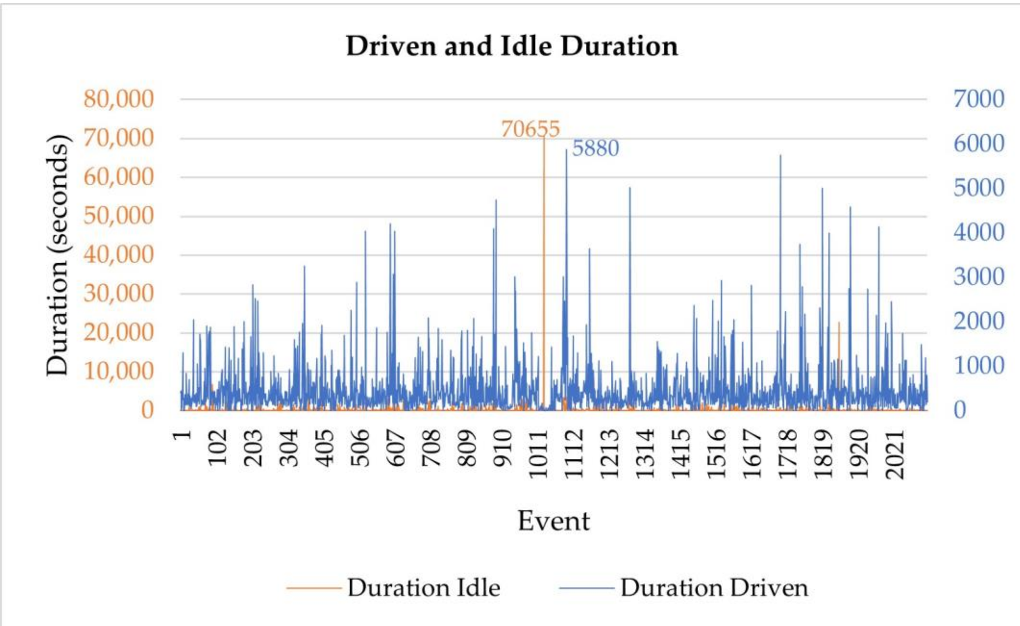


Figure 17. Plot of idle and driven times of the recorded trips.

Further, Table 7 compares the driven and idle times of the trips statistically. It was observed that the average driven time was higher than the average idle time, suggesting that this vehicle was in constant use.

Table 7. Descriptive statistics comparing driven and idle times.

Driven Duration (Seconds)				Idle Duration (Seconds)			
Mean	**Max.**	**Min.**	**Total**	**Mean**	**Max.**	**Min.**	**Total**
896	5880	0	949,425	520	70,655	0	550,496

The start and end SOC are monitored and recorded for all the trips as shown in Figure 18. It was observed that the start SOC ranges between 10% to 100% for the recorded trips. And the end SOC ranges between 8% to 100% for the recorded trips.

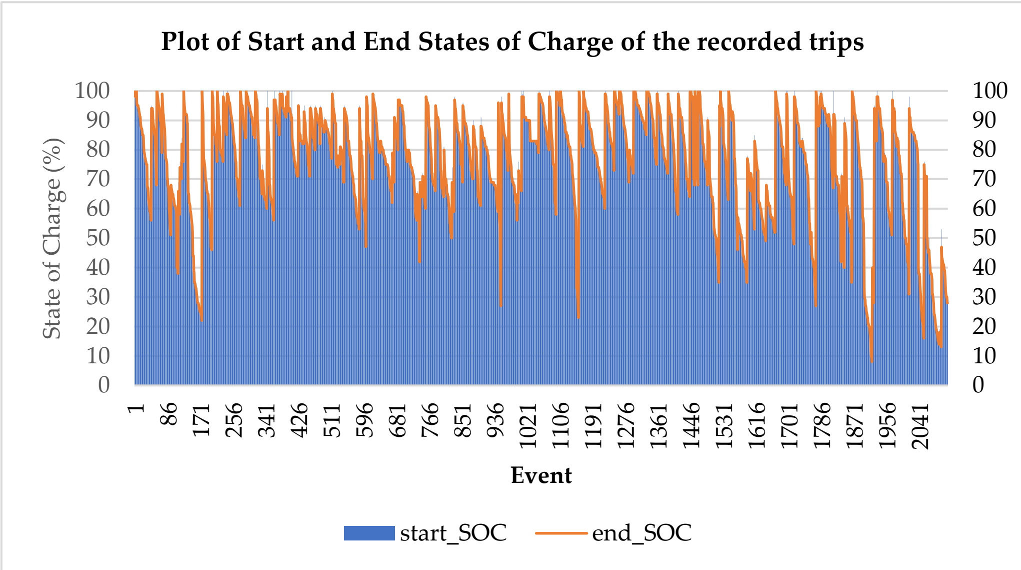


Figure 18. Plot of start and end States of Charge of the recorded trips.

The distance travelled by the vehicle in each of the trips was recorded as shown in Figure 19. Due to the low resolution of the distance field, the distance_gps field was calculated by us using the latitude and longitude to allow greater accuracy. The average distance travelled by the vehicle was 1.5 miles and the total distance travelled was 3247.5 miles. The minimum travelled distance recorded was 0 miles for empty trips. It was observed that the majority of trips were urban in nature. A total of 212 empty trips were also recorded, and a negligible number of rural and motorway trips were recorded.

The energy consumed by the recorded trips was analysed and plotted as shown in Figure 20. It was observed that the energy consumed ranged between 0 and 6.3 kWh. It was observed that most of the trips consumed less than 1 kWh, and just a few of them needed more than 4 kWh.

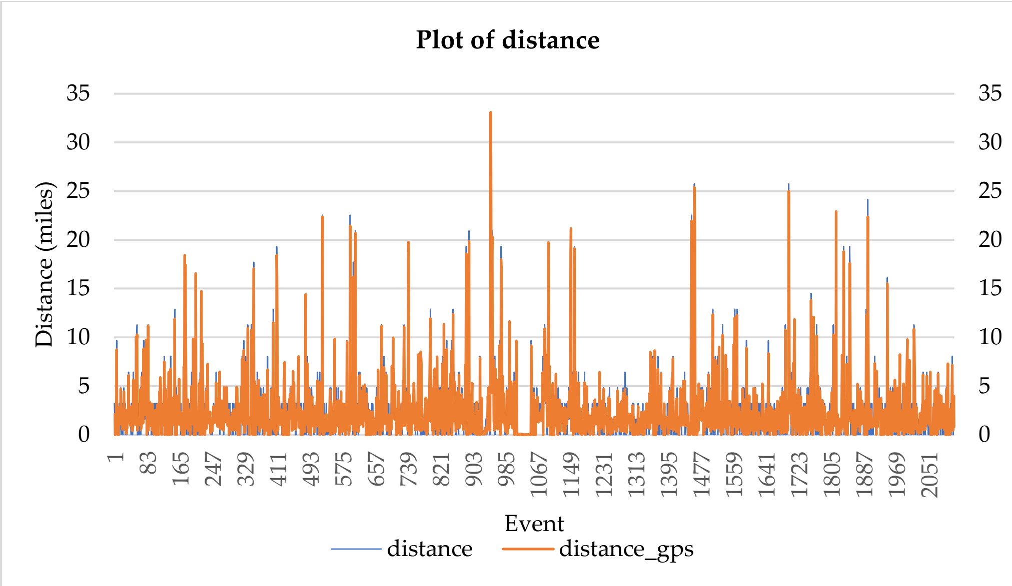


Figure 19. Plot of distance travelled.

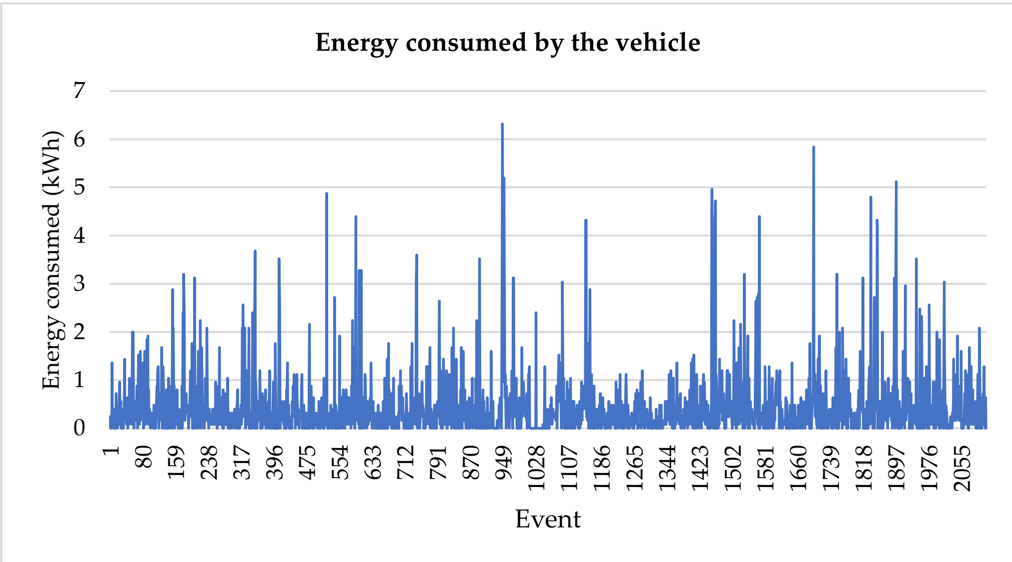


Figure 20. Plot of energy consumed by the vehicle per trip.

Further, Figure 21 represents the monthly distribution of recorded trips. The number of recorded trips was relatively low for August because the vehicle was down for repair from 6 August 2021 to 2 September 2021.

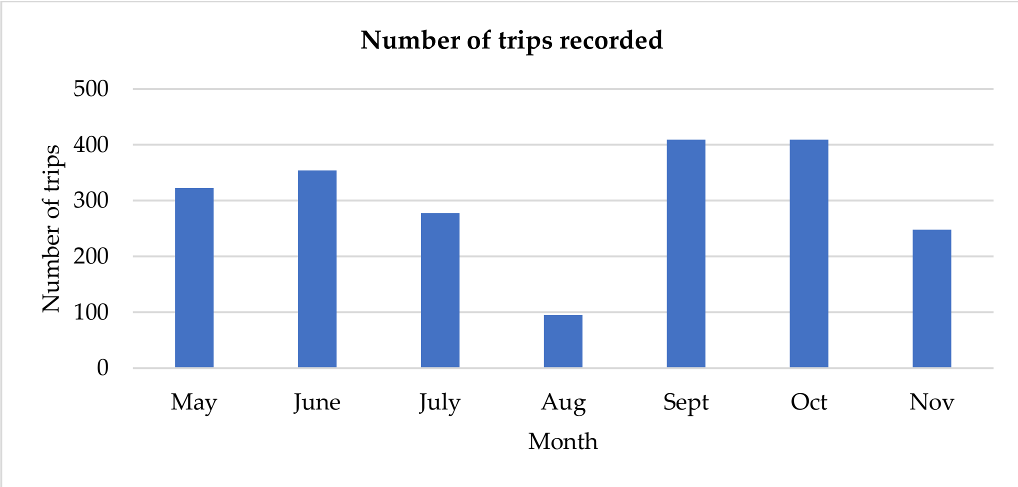


Figure 21. Month-wise distribution of trips.

6. Opportunities and Benefits of Bidirectional Charging

The opportunities and benefits of bidirectional charging were analysed in stage III as reported in Section 4. The feasibility and benefits of V2G, such as flattening of the load curve and carbon savings, were analysed critically with the help of the stage I and stage II results.

6.1. Opportunities of Charging and Discharging

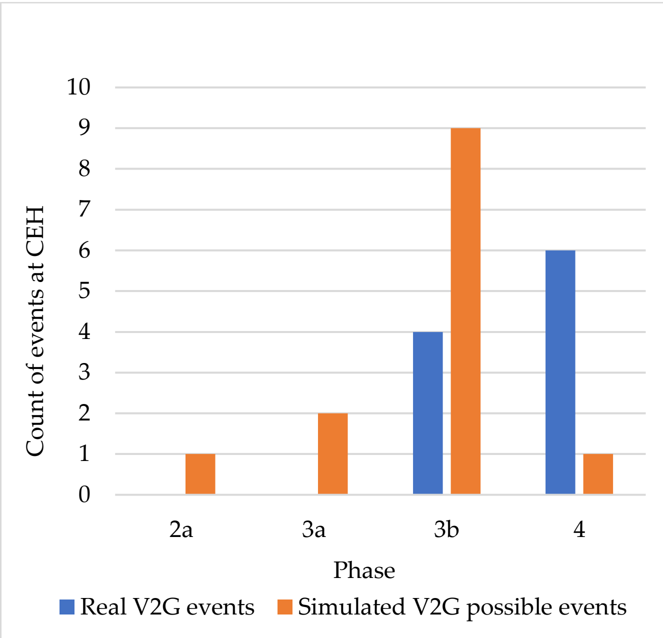
According to Bui, T.M. et al. [21] a preconditioned strategy for charging and discharging the vehicles could mitigate the battery ageing from 8.6% to 12% in a year with continual operation of an electric vehicle compared to a standard charging approach. For EV-elocity, the team from WMG University of Warwick defined the charging parameters applied on phase 4 based on their research outcomes. These parameters included asking the users to register the plug-in time, plug-out time, and the percentage state of charge desired at the end of the V2G session. Then, the charger took the state of charge to 50%, holding at this level for as long as possible then taking the state of charge to the required percentage at the plug-out time. Therefore, in the following analysis it is assumed that the probability of V2G is computed based on the criterion that the EV is available for V2G if the SOC is more than or equal to 50%. This criterion is used just to give an estimation of the possibility of V2G in a very opportunistic and optimistic way from the recorded data. In reality, some other factors such as the charging and discharging cycles and the daily routine of the vehicle will also play a role in quantifying the possibility of V2G.

Table 8 reports the probability of the EV being available for V2G before and after charging. It was observed that the probability of the V2G before charging is 0.25 and the probability of V2G after charging is 0.81 for Creative Energy Homes. The probability of V2G before and after charging for Hallward Library were 0.69 and 0.82, respectively.

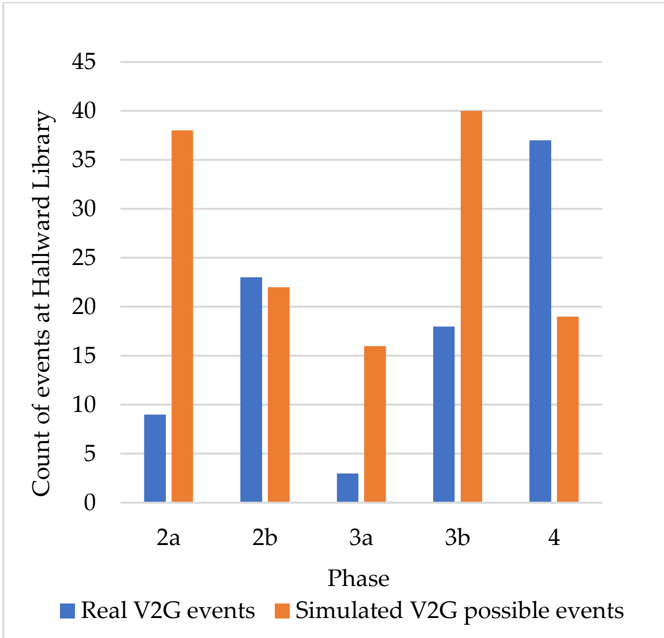
Table 8. Probability of V2G before and after charging.

Site	Probability of V2G before Charging	Probability of V2G after Charging
CEH	0.25	0.81
Hallward Library	0.69	0.82

In Figure 22, the distribution of possible events according to the phases is presented. For instance, the vehicle charging at Creative Energy Homes (Figure 22a) had nine possible events during phase 3b, but only four V2G events occurred. Conversely, the simulated possible events during phase 4 resulted in one V2G event, while in real life there occurred six V2G events. In the case of Hallward Library (Figure 22b), all phases presented V2G events; however, the phase with a closer similarity between real and simulated events was phase 2b. Phase 3b had similar outcomes between CEH and HL, as both were overestimated in the simulation and had less than half of the real events.



(**a**)



(**b**)

Figure 22. Distribution of V2G possible events over different phases for Creative Energy Homes (**a**); (**b**) Distribution of V2G possible events for Hallward Library.

6.2. Likelihood of Vehicle Charging and Trip Behaviour

The behavioural pattern of the vehicle was analysed in terms of likelihood of the vehicle being plugged in and likelihood of the trip start time. The likelihood of the vehicle being plugged in was computed per hour for 24 h of a day as shown in Figure 23a for Creative Energy Homes. It was observed that the likelihood of a vehicle being plugged in was highest for around 9:00 a.m. for Creative Energy Homes. Similarly, Figure 23b shows the likelihood of a vehicle being plugged in at the Hallward Library site. It was observed that the likelihood of a vehicle being plugged in was more scattered for the Hallward Library site than for Creative Energy Homes site. It was observed that the highest likelihood of the vehicle being plugged in occurred at 3:00 p.m.

The likelihood of trip start times was computed for the fleet vehicle monitored at the Hallward Library site and plotted as shown in Figure 24. At 9 a.m. the vehicle obtained the highest likelihood for the start of a trip. Moreover, the likelihood of the start of a trip was distributed over 24 h for this vehicle as the vehicle is commercial in nature. However, the likelihood of start time decreased during the night.

While analysing the trip datasets, it was observed that there were some instances where the standing time between two consecutive trips was long. Those events were analysed quantitatively in this section. Table 9 reports the statistical data related to the standing time between two consecutive trips. It was observed that the average standing time between two consecutive trips was 1 h 57 min, and the total standing time was 20 days 15 h 25 min.

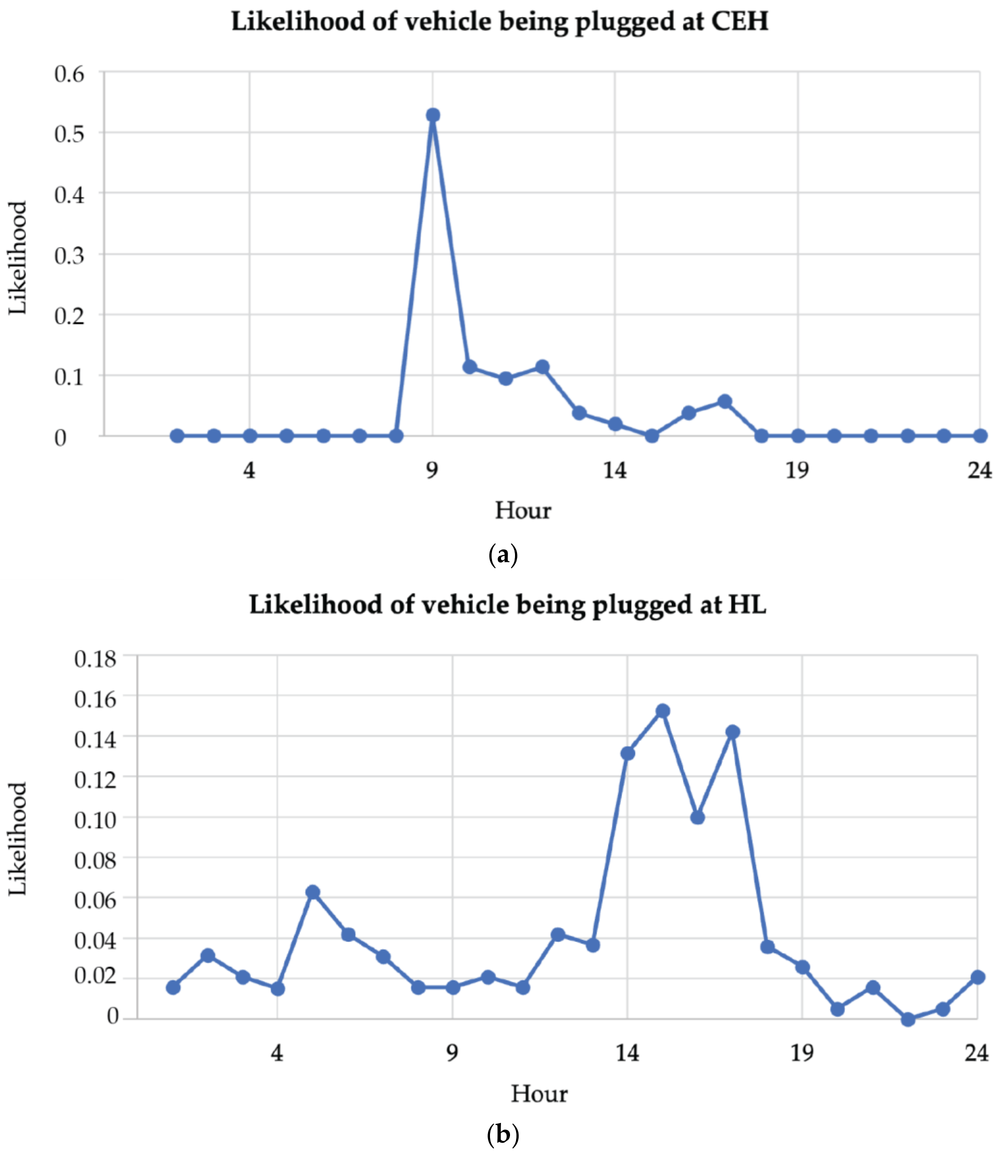


Figure 23. Likelihood of vehicle being plugged in for (**a**) CEH and (**b**) Hallward Library.

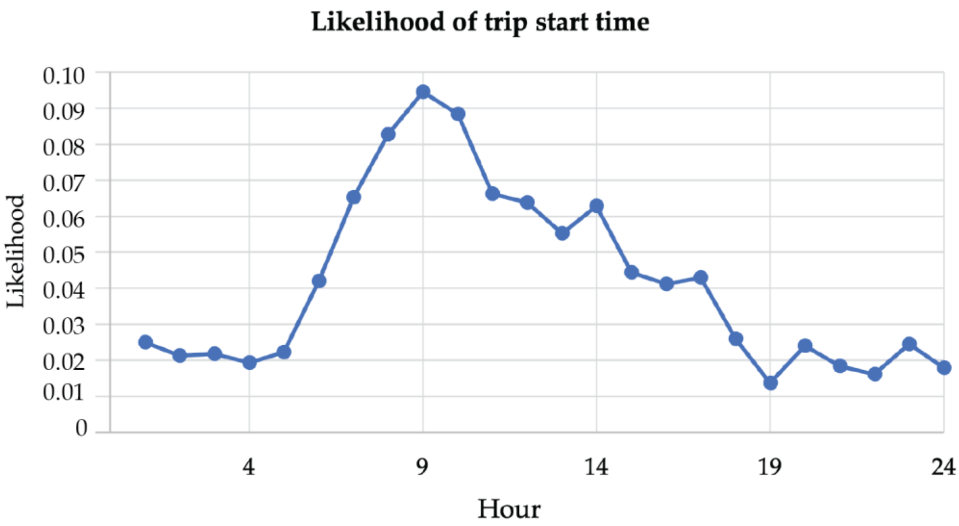


Figure 24. Likelihood of trip start time.

Table 9. Descriptive statistics related to standing time between two consecutive trips.

Mean	Maximum	Minimum
1 h 57 min	6 days 22 h 19 min	0 h

Table 10 reports the likelihood of events with standing time greater than 30 min, between 30 and 60 min, and more than 60. It was observed that the likelihood of a standing time greater than 30 min was 0.30, likelihood of a standing time between 30 and 60 min was 0.13, and likelihood of a standing time greater than 60 min was 0.17.

Table 10. Likelihood of standing time.

Standing Time	Likelihood
Greater than 30 min	0.30
Between 30 min to 60 min	0.13
Greater than 60 min	0.17

The events reported with a standing time between two consecutive trips of more than 30 min were separated out for further analysis. Figure 25 shows the locations of the vehicle when the standing time between consecutive trips was more than 30 min. The red dots in Figure 25 represent the locations of the vehicle. Blue and green dots represent the location of Creative Energy Homes and Hallward Library, respectively. It was observed that there are many places on campus where the vehicle stops for more than 30 min, which could suggest strategic location for future chargers.

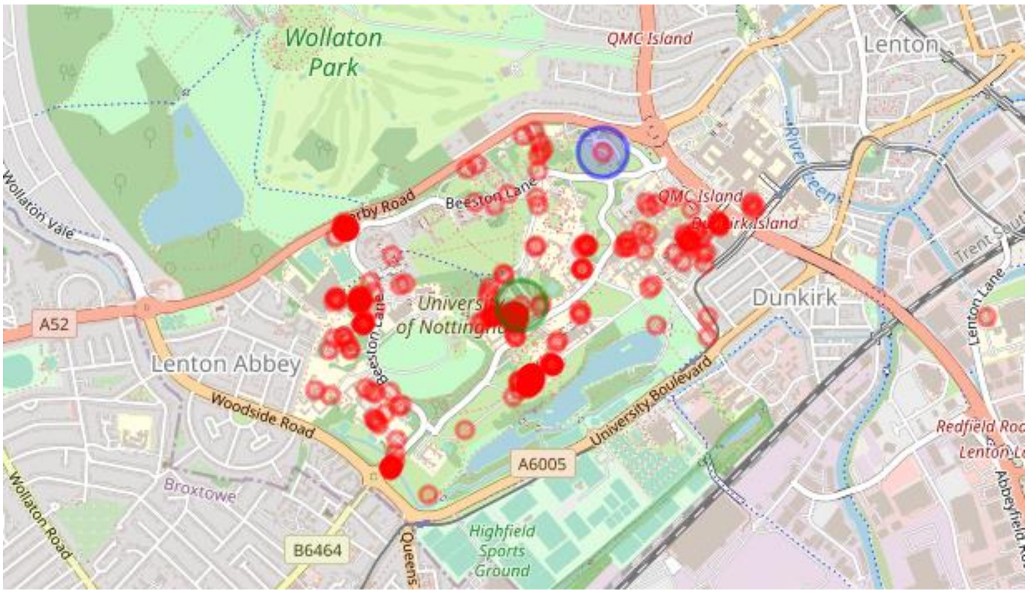


Figure 25. Locations of the vehicle with standing time more than 30 min. In blue is marked the location of the Creative Energy Homes charger, and in green the location of the Hallward Library charger. The red colour represents the places where the vehicles remain idle.

In Figure 26, the distance of the vehicle, while standing, to the chargers is presented. As the vehicle is used for patrolling around campus, the distances to the chargers were short. However, there were a few events when the vehicle was outside of campus and the distances increased.

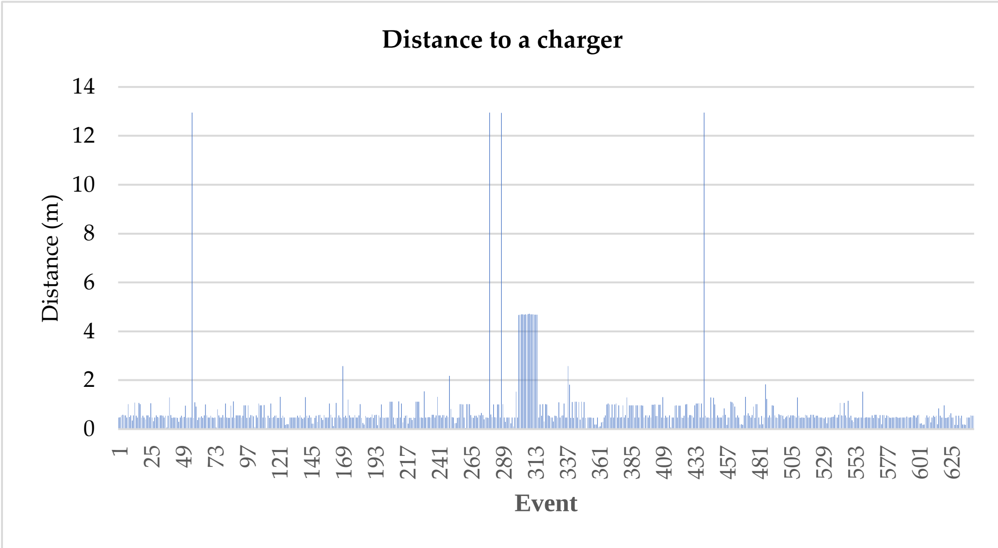


Figure 26. Distance between standby locations and chargers.

Further, Table 11 reports the likelihood of a charger located at a distance of 100 m, as well as 500 m when the vehicle standing time is more than 30 min. It was observed that the likelihood of the charger being within a distance of 100 m was as low as 0.01. And the likelihood of charger within a distance of 500 m was 0.53, which is relatively high.

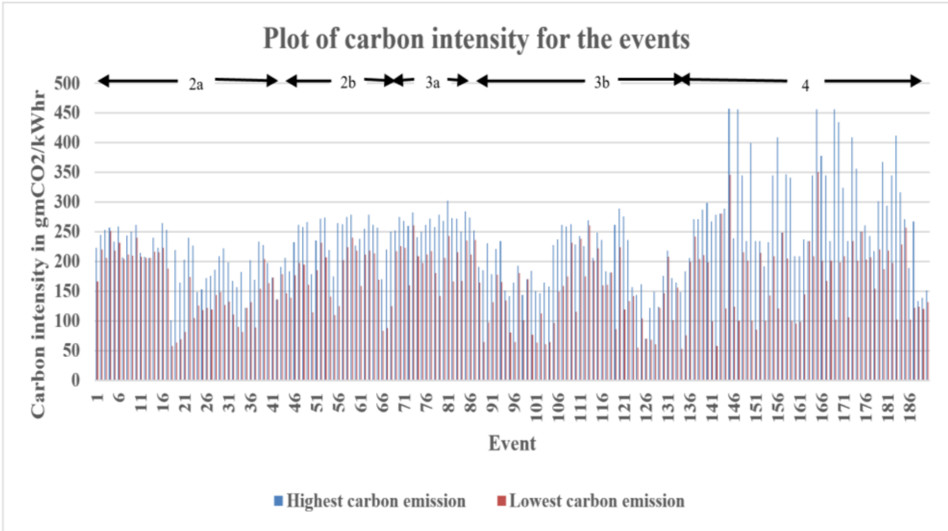
Table 11. Likelihood of distance between charger location and standby location of vehicles when standing time is more than 30 min.

Distance to the Charger	Likelihood
Likelihood of charger at 100 m	0.01
Likelihood of charger at 500 m	0.53

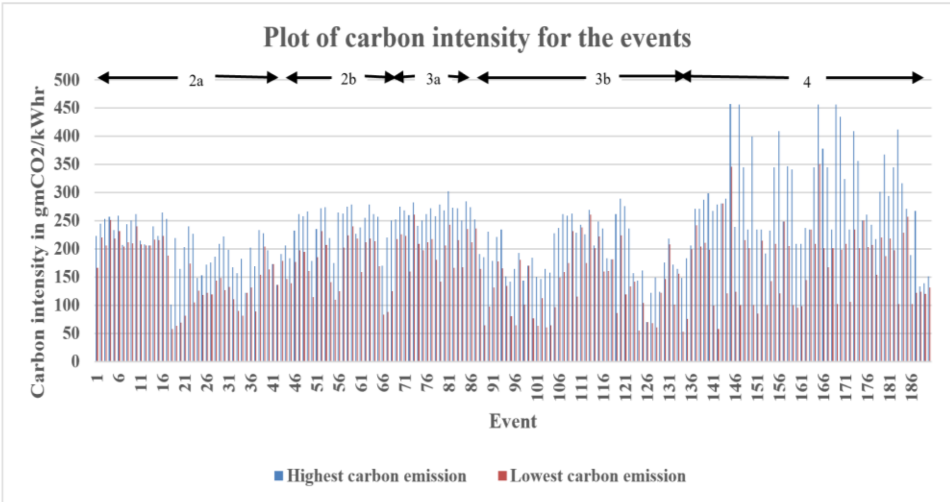
6.3. Carbon Savings

Further, the carbon savings by participating in V2G were also analysed. The carbon-intensity data was taken from the National Grid ESO [36]. Figure 27 shows the plot of carbon intensity for the events at Creative Energy Homes and Hallward Library. The analysis corresponds to the highest and lowest scenarios for the carbon intensity registered for each event. It was observed that during phases 2 and 3 the carbon emissions were lower than the emissions from phase 4. And the phase with by far the lowest emissions was phase 3b, in which a Dynamic Carbon Optimisation Schedule was tested. It can be noted that phases 2 and 3 were very similar in terms of the lowest and highest emissions, which may suggest that cost and carbon emissions from electricity are highly related. On the other hand, a strategy to reduce battery ageing without considering the carbon emissions from electricity could increase the emissions.

Table 12 reports the savings in carbon emissions achieved by discharging for both sites, assuming scenarios of high and low emissions. For the case of CEH, the highest level of carbon emissions obtained was 52,600 $gmCO_2$, which would be compensated for by the saving emissions from discharging using V2G by 14,844 $gmCO_2$. This represents a saving of 28.2% over the emissions of charging this vehicle. For Hallward Library, the highest carbon emissions of the site would be 823,631 $gmCO_2$, with the option of saving up to 372,346 by using V2G. The saving would represent 45.2% of the emissions of this vehicle.



(**a**) Plot of carbon intensity for the events at CEH for different phases



(**b**) Plot of carbon intensity for the events at Hallward Library for different phases

Figure 27. Plot of carbon intensity for the events.

Table 12. Carbon savings achieved by discharging.

Creative Energy Homes		
	Highest	Lowest
Net carbon emission (gmCO_2)	52,600	46,293
Savings in carbon emissions by discharging (gmCO_2)	14,844	13,095
Hallward Library		
Net carbon emissions (gmCO_2)	823,631	498,498
Savings in carbon emissions by discharging (gmCO_2)	372,346	211,089

6.4. Energy Usage Optimisation

A previous analysis of the role of EV-charging technologies in decarbonising the transport and energy systems was conducted by Waldron et al. [22]. The authors evaluated the energy demand of three buildings at the campus of the University of Nottingham and evaluated possible scenarios for vehicle-to-grid systems. This study concluded that unmanaged charging of EVs on campus would increase the energy demand and the CO_2 emissions of the grid. The study proposed a V2G-charging scheme that would help to reduce CO_2 emissions by charging the vehicles when the carbon intensity of the energy grid was low and discharging them when the carbon intensity was high [22].

To understand how EVs and V2G can support energy grid and reduce carbon emissions in a domestic environment, load-curve data from a typical domestic household of the UK is used as a reference [37]. The computation simulated a household with two vehicles available for vehicle-to-grid usage and a constant power export of 5.98 kWh per vehicle.

Figure 28 shows how V2G during peak-load periods could support flattening the load curve of a typical household in the UK. It must be noted that the results related to the flattening of the load curve are assumed values and not real values.

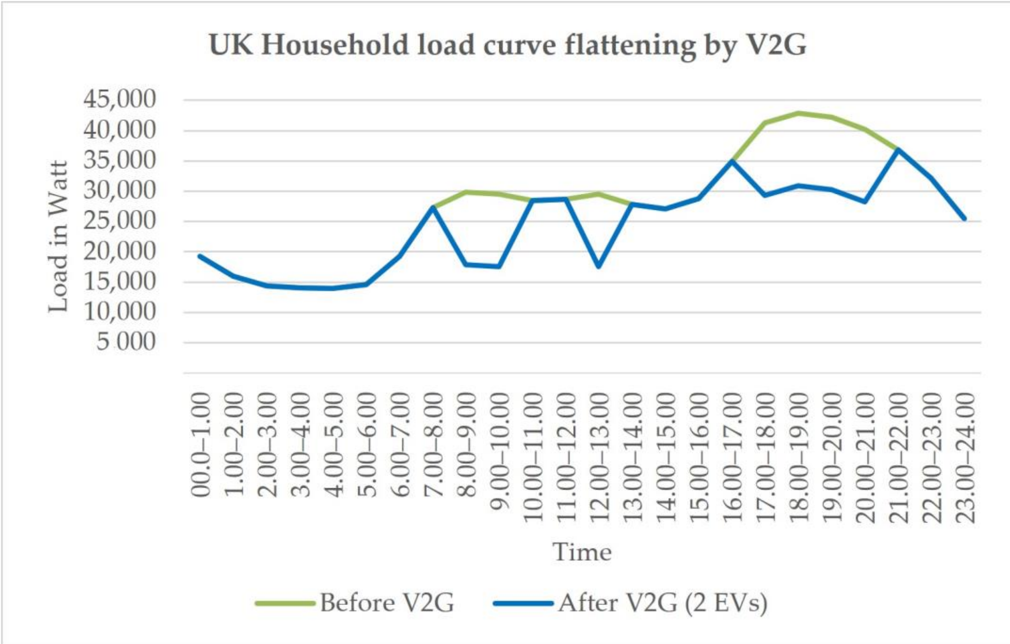


Figure 28. UK Household-Load-Curve Flattening by V2G.

7. Conclusions

The charging and trip datasets of the EV-elocity demonstration sites at UoN campus were analysed in this work. It was found that the probabilities of V2G before charging for Creative Energy Homes and Hallward Library were 0.25 and 0.70, respectively, thereby indicating further potential for V2G in real-world scenarios. However, some other factors such as charging and discharging cycles, daily routine of the vehicle, and unexpected events inducing behavioural changes such as a pandemic play important roles when quantifying the possibility of V2G. While analysing the trip datasets, it was observed that there are some instances where the standing time between two consecutive trips is long with average standing time between 1 h 57 min and the total standing time was 20 days 15 h 25 min. The events reported with standing time between two consecutive trips of more than 30 min were separated out for further analysis and it was checked whether there was a charger nearby for those standing events. It was found that for 52.6% of events the vehicle was standing at less than 500 m from the charger location, thereby indicating lack of interest or awareness of the vehicle driver about discharging using V2G. The energy and carbon savings by V2G were analysed. The analysis per phase indicated that the phase with lowest carbon emissions was that using the Dynamic Carbon Optimisation Schedule, which was operated using CrowdCharge. It was also observed that phase 4 presented the highest carbon intensities, suggesting that the battery ageing optimisation models should include the carbon optimisation to avoid incremental of carbon emissions of the system. It was observed that by V2G, 28.22% of carbon savings was achieved for Creative Energy Homes and 45.20% for Hallward Library considering the highest carbon-intensity scenario. However, it must be noted that the size of the two buildings is very different. Simulated calculations of V2G reported the capacity of this technology to flatten the load–household curve during peak time hours. This paper quantifies the feasibility of a V2G scheme in a real-world environment thereby analysing the charging/discharging and the vehicle activities, to report the opportunities and benefits of bidirectional V2G. However, future work could integrate multiple sources of data, such us the university power-network data and detailed data from renewable sources onsite, as this would provide a wider understanding of the benefits of vehicle-to-grid systems. Additionally, future work should address the integration of EV batteries as a medium of storage in local energy communities to investigate other benefits of vehicle-to-everything (V2X) systems from the user perspective.

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Data Availability Statement: The domestic-household–load curve of UK data was analysed using the data from: Palmer, J. and Terry, N. (2014). Powering the Nation 2: Electricity use in homes, and how to reduce it. Department of Energy and Climate Change (accessed on 20 August 2022). The grid carbon-intensity analysis included data published by the Carbon Intensity API available at https://carbonintensity.org.uk/ (accessed on 2 September 2022).

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Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The abbreviations used in this paper are shown below:

Abbreviation	**Meaning**	**Units**
CO_2	carbon dioxide	
distance	distance of the trip according to the telematics system	miles
distance_gps	calculated distance of the trip using the latitude and longitude	miles
duration charge/discharge	duration of charging/discharging the electric vehicle battery	minutes
duration_driven	duration of a driving event	minutes
duration_idle	duration of an idle/parking event	minutes
end_SOC	final battery state of charge after charging	kW
EVs	electric vehicles	
gmCO_2	gram of carbon dioxide	
kW	kilowatt	

kWh	kilowatt per hour	
PHEV	plug-in hybrid electric vehicle	
SOC	battery state of charge	kW
start_SOC	initial battery state of charge before charging	kW
V2G	vehicle-to-grid	
V2X	vehicle-to-everything	
V2B	vehicle-to-building	
V2H	vehicle-to-home	

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