

# Battery-assisted Electric Vehicle Charging: Data Driven Performance Analysis

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**Abstract**—As the number of electric vehicles rapidly increases, their peak demand on the grid becomes one of the major challenges. A battery-assisted charging concept has emerged recently, which allows to accumulate energy during off-peak hours and in-between charging sessions to boost-charge the vehicle at a higher rate than available from the grid. While prior research focused on the design and implementation aspects of battery-assisted charging, its impact at large geographical scales remains largely unexplored. In this paper we analyse to which extent the battery-assisted charging can replace high-speed chargers using a dataset of over 3 million EV charging sessions in both domestic and public setting in the UK. We first develop a discrete-event EV charge model that takes into account battery capacity, grid supply capacity and power output among other parameters. We then run simulations to evaluate the battery-assisted charging performance in terms of delivered energy, charging time and parity with conventional high-speed chargers. The results indicate that in domestic settings battery-assisted charging provides 98% performance parity of high-speed chargers from a standard 3 kW grid connection with a single battery pack. For non-domestic settings, the battery-assisted chargers can provide 92% and 99% performance parity of high-speed chargers with 10 battery packs using 3 kW and 7 kW grid supply respectively.

**Index Terms**—electric vehicles, charging stations, systems simulation

## I. INTRODUCTION

Electric vehicles (EVs) represent a small but rapidly growing transportation segment due to lower carbon emissions, smaller running costs as well as higher energy efficiency. As battery costs decline, the EVs become more affordable and are set to replace traditional fossil-fuel based internal combustion engine (ICE) vehicles in the near future. At the same time, rapid charging of EVs remains a major challenge due to the need for high-powered grid connections in both domestic and urban settings [1]. Hence, the EV owners and charging station operators are required to upgrade their grid supply capacity, which is expensive to set up and increases the peak demand on electric grid.

Recently, battery-assisted EV charging technology has been developed, where a large capacity battery is integrated into an EV charge point to accumulate energy during off-peak hours and in-between charging sessions and boost-charge the EV at a higher speed than is available from the grid. For example, a power-boost technology was developed by [2], which uses battery-stored energy to provide fast, rapid and ultra-fast charging from 3-7 kW grid-supply. A system was developed

by [3], which can charge a 30 kWh car in 15 minutes using Li-ion battery bank using low power from the grid. The research led to a number of successful deployments in domestic and commercial sectors [2] [4]. At a national infrastructure scale, the UK National Grid plans to deploy a network of batteries across 45 battery sites near towns or major roads. The £1.6 billion network will be used for rapid EV charging stations, support electric hub depots and will have capability to support 350 kW EV chargers. The system will connect directly to National Grid's extra-high-voltage transmission system [5].

Prior work on battery-assisted charging addressed the design, performance evaluation of standalone chargers or its components [6] [7] [8]. In particular, Aziz et al [9] compare co-ordinated charging [10], demand response [11] and battery-assisted charging technologies and show that battery-assisted charging can enable fast charging whilst also minimising the stress experienced on the electrical grid that occurs when many electric vehicles are simultaneously charged. While prior work on battery-assisted charging investigated the design, optimisation and performance analysis of individual charge points, its potential impact on charging performance at scale, taking into account the actual charge point usage requires further investigation.

In this paper, we investigate the impact of battery-assisted charging on electric peak demand through a combination of simulation and a statistical analysis of a charge point usage dataset that contains more than 3 million charging sessions in domestic and urban settings in the UK. We first develop a formal model that describes a system state based on the battery capacity, power available from grid and maximum charge output. The model is then driven by the charging events from the dataset to understand the EV charging performance in terms of charging duration, dispensed energy and battery utilisation under domestic and public deployment scenarios for a range of energy storage capacities. To the best of our knowledge this is the first work analysing the performance of battery-assisted EV charging at a large geographical scale.

## II. BATTERY-ASSISTED EV CHARGING

Depending on charging current, the Electric Vehicles charging speeds are categorised into slow, fast and rapid.

- Slow chargers connect to a standard 3-pin domestic socket. The standard UK socket is rated at 13 A but

normally provides 10 A (2.3 kW) to reduce the risk of overheating under continuous load.

- Fast chargers connect to a dedicated socket and deliver 7-22 kW over a single or three phases. When using a fast charger, the charging speed will be limited by the power of vehicle's own onboard AC-to-DC converter. Most cars on the market currently support single-phase max 16-32 A charging (3.7-7.2 kW) while the newer cars support charging with 2 or 3 phases (11 kW and 22 kW respectively).
- Rapid chargers connect to a dedicated socket and deliver 43-120 kW. Rapid chargers bypass the onboard charger of an electric vehicle and supply the DC current directly to the EV battery. DC charging stations are much more complex and more expensive than AC charging stations and require high powered electric supply point.

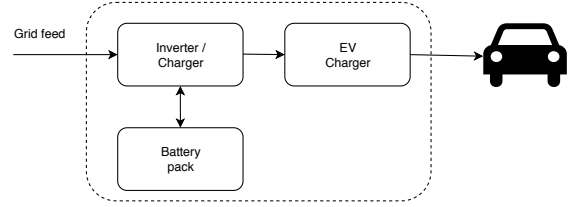


Fig. 1: System Diagram.

TABLE I: EV charging speed comparison

Supply type / Charger rating	AC/DC	Rated power	Time to charge
Regular socket, 10 A	AC	2.3 kW	17.4 hours
Single phase, 32 A	AC	7.3 kW	5.5 hours
3 phase, 16 A per phase	AC	11 kW	3.6 hours
3 phase, 32 A per phase	AC	22 kW	1.8 hours
3 phase, 60 A per phase	AC	41 kW	58 minutes
3 phase, DC	DC	50 kW	48 minutes
3 phase, DC	DC	120 kW	20 minutes

### III. SYSTEM MODEL

#### A. Battery-assisted charging system

A battery-assisted charging system consists of a high capacity battery bank, a hybrid charging inverter and an EV charger as shown on Fig. 1. A brief description of each component is provided below.

*Battery:* The battery accumulates energy from grid in-between EV charging sessions or when the EV charging speed is lower than available from the grid. The battery has capacity of  $B_{storage}$  and provides a continuous output power  $P_{battery}$  to the load. Several battery packs can be combined to increase capacity and the output current.

*Hybrid charging inverter:* This component converts the AC power to DC for charging a storage battery, and then back to AC whenever battery is used to boost output power. The hybrid inverters with pass-through capability have the ability to power the load from AC input while redirecting any excess to the battery. For example, Victron Quattro range of inverters which use battery-assist feature to combine AC mains and battery power have been successfully used for EV charging systems [12].

*EV charger:* EV charger communicates with the electric vehicle using a control pilot line to negotiate maximum allowable charging current, detect presence of the vehicle and control start and end of a charging session. The charging station can provide an output of  $P_{battery} + P_{grid}$  unless the battery is depleted in which case the maximum output power reduces to  $P_{grid}$ .

*Electric Vehicle:* The maximum charging speed is limited by the vehicle's own AC/DC converter. Early EV models support single-phase 16-32 A charging (3.7 kW-7.2 kW), while newer car models support 11 kW and higher. The charging duration depends linearly on the charging current and therefore can be very long on a standard 3 kW supply. Table 1 compares approximate durations to charge 40 kWh battery using different charging speeds.

#### A. Charger model

The EV storage battery state is described by the following system of equations:

$$B(t+1) = B(t) + P_{gridfeed} \times T - EV(t) \quad (1)$$

$$0 \leq B(t) \leq B_{storage} \quad (2)$$

$$EV(t) \leq B(t) + P_{gridfeed} \times T \quad (3)$$

$$EV(t) \leq (P_{gridfeed} + P_{battery}) \times T \quad (4)$$

$$EV(t) \leq P_{EVmax} \times T \quad (5)$$

Where  $B(t+1)$  is the amount energy stored in a battery at the start of timeslot  $t+1$ , which depends on the amount of energy  $B(t)$ , energy received from grid  $P_{gridfeed} \times T$  and energy used for EV charging  $EV(t)$  in timeslot  $t$ . Here, we assume that the grid has a constant power capacity  $P_{gridfeed}$ . Constraint (2) reflects the maximum battery capacity,  $B_{storage}$ . Constraint (3) ensures that in any single timeslot, the amount of energy spent on EV charging does not exceed the combined energy from the grid and the battery. The power supplied by grid,  $P_{gridfeed}$  can be 2.3 kW for domestic chargers using UK 3-pin socket and ranges from 3 kW to 100 kW+ for dedicated EV charging stations. Constraint (4) limits the delivered power to a combined power of grid and a battery pack  $P_{gridfeed} + P_{battery}$ , which can be increased by connecting multiple batteries in parallel. Constraint (5) limits the EV charging speed to a maximum EV charging power capability,  $P_{EVmax} \cdot T$  is a timeslot duration, which without loss of generality is assumed to be short enough that it contains no more than a single charging session. The battery pack charges whenever an EV charger is idle or is supplying less than  $P_{gridfeed}$  to EV. In the event that more energy is needed than the grid can supply, the charger's battery must be used. The maximum supplied power is also limited by the capacity of battery pack and the inverter.

### IV. EV CHARGE POINT DATASET

The experimental evaluation is based on electronic charging station (ECS) usage datasets in the UK, provided by the

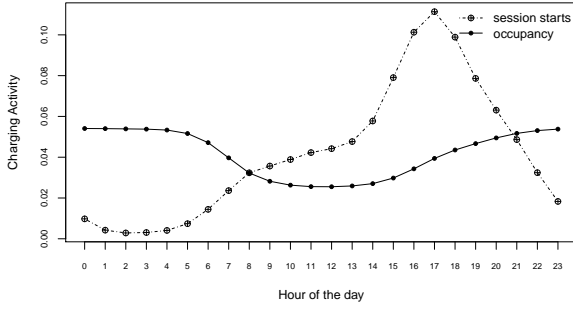


Fig. 2: Domestic chargers diurnal activity distribution.

Department of Transport’s Energy and Environment statistics [13] [14]. Each dataset contains raw data on amount of energy supplied, and plugin duration per charging event for both domestic charge points and non-domestic (local authority) settings in the UK. The data analysis has been performed in *R* statistical environment [15].

#### A. Domestic charge point dataset

The domestic charge point dataset contains 3.17 million charging sessions from 25126 domestic chargers collected in 2017 in the following format:

EventID	CPID	StartDate	StartTime	EndDate	EndTime	Energy	PluginDuration
3177742	AN21771	31/12/2017	23:59:23	01/01/2018	18:20:23	8.8	18.35
16679268	AN04715	31/12/2017	23:59:00	01/01/2018	00:03:00	10.2	0.066

The session charging speed, computed separately by dividing the dispensed energy by the plugin duration, varies within the same charge point as plugin duration can be longer than the actual charging duration. To eliminate this factor from our analysis we introduced an *effective charging duration* metric as ratio of dispensed energy to the maximum charging speed within the given EV charge point as described in Section V-A. Table II shows the distribution of maximum charging speeds for various charge speed intervals, which can provide an idea about the number of EVs in each charging speed category.

For domestic charge point analysis, we consider chargers with a maximum charging rates between 3 kW and 22 kW, which represented 21009 charge points in total. As domestic chargers can typically charge only one EV at a time, the overlapping sessions within the same charge point, which represented 1.7% of all charging events have been removed from the analysis.

TABLE II: Distribution of charging session speeds. Domestic chargers

Session speed, E(kW)	#CPs with this Max rate	#CPs with this median rate
$0.0 \leq E < 1.0$	393	11572
$1.0 \leq E < 2.3$	691	8755
$2.3 \leq E < 3.0$	1292	1871
$3.0 \leq E < 7.0$	15095	2707
$7.0 \leq E < 22.0$	5887	186
$22.0 \leq E < 100.0$	1348	26
$100.0 \leq E$	420	9

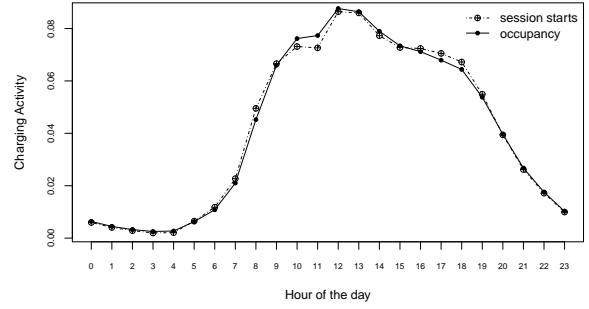


Fig. 3: Local authority chargers diurnal activity distribution.

Figure 2 shows that the charging session activity exhibits a strong temporal pattern. The charging sessions are typically initiated between 1pm and 9pm with vehicles remaining connected until early in the morning. As most sessions are relatively long in duration (the mean and median plugin durations are 12.44 and 10.72 hours respectively), the distribution EV charger occupancy is more spread throughout a day compared to the distribution of session start times. The battery-assisted charging systems can accumulate energy during relatively quiet periods and release it during the peak hours to shorten the charge duration or reduce the peak load on the grid.

#### B. Local authority charge point dataset

The local authority dataset contains 108746 charging sessions from 237 fast and rapid chargers deployed across 27 local authorities in England [14]. According to dataset, the vast majority of charge points are capable of drawing more than 22 kW. For local authority charge point analysis, we consider chargers with a maximum charging rates between 3 kW and 100 kW, which represented 233 charge points in total. For the purpose of this study, we exclude charge points with multiple connectors and in cases where the number of connectors is not specified, assume that the charge point supports a single EV only. Table III shows the distribution of charging and median speeds for public charge points.

TABLE III: Distribution of charging session speeds. Local authority chargers

Session speed, E(kW)	#CPs with this Max rate	#CPs with this median rate
$0.0 \leq E < 7.0$	2	8
$7.0 \leq E < 22.0$	1	141
$22.0 \leq E < 100.0$	230	88
$100.0 \leq E$	4	0

Fig 3 shows the hourly distribution of dispensed energy and charge duration with most sessions initiated between approximately 7am and 11pm. Similarly to domestic charging, the behaviour of local authority chargers exhibits a strong temporal pattern although the peak usage is more spread throughout a day. Due to relatively short average charge session durations, both occupancy and session start distributions are similar unlike those for domestic chargers (the mean and median plugin durations are 38.1 and 29 minutes respectively).

## V. EXPERIMENTAL RESULTS AND DISCUSSION

The goal of experiments is to evaluate the impact of battery-assisted scheme on charging performance in terms of mean delivered energy and charge duration when charge points are powered through standard 3 kW grid supply. The evaluation shows an extent to which battery-assisted charging can provide parity with existing rapid chargers in terms of delivered energy.

The charge points are assumed to be equipped by a battery pack with specifications similar to Tesla PowerWall 2 [16], which has 13.5 kWh capacity and 5 kW sustained power output per battery. Several battery packs can be combined in parallel to increase storage capacity and output power. We further assume that the EV can charge at a rate supplied by the charge point. The assumption is only used to estimate effective charging durations as explained later and does not affect the performance results in terms of amount of dispensed energy.

### A. Domestic Charger Analysis

Table IV shows the amount of delivered energy depending on the number of batteries. Interestingly, a charge point without any batteries can deliver 94.18% of raw energy. This is because in domestic charging, the vehicle often remains connected to the charger for longer than the actual active charging duration and therefore reducing a grid supply to 3 kW does not significantly impact the amount of delivered energy. A single battery pack increases the proportion of delivered energy to 99.3% while reducing the effective charging duration from 2.87 to 1.28 hours. Subsequent increase in number of batteries brings further improvements in effective duration but not in terms of energy delivered. In other words, given the amounts of dispensed energy and relatively long plugin durations, downgrading the charge point grid connection to 3 kW does not significantly impact the charging performance in terms of delivered energy. On the other hand, higher charging speed may encourage the drivers to charge more at home, as the median delivered energy is correlated with EV charge speed as shown in Table V.

To estimate the impact on the actual charging duration, we obtain EV charging capability as the maximum charging session speed within a given charge point, assuming it serves the same vehicle throughout a year. We then define *effective charging duration* as the ratio of delivered energy to the EV charging speed. As can be seen in Table IV, the effective duration for zero batteries scenario is 2.87 hours. As the number of batteries increases, the effective duration reduces to 0.42 hour due to higher charging speed provided by the charge point. Finally, the session parity rate shows a proportion of charging sessions that received the same amount of energy as in raw charging. As can be seen in Table IV, the session parity rate ranges from 98.89 to 99.77 for a single and 4 batteries respectively.

*Battery utilisation:* The battery utilisation in terms of charge-discharge cycles is computed as the total battery discharge for all sessions within each charge point and dividing that by the battery pack capacity. The minimum, maximum and average battery cycles are 0, 482 and 49 respectively for

TABLE IV: Performance of Domestic Chargers

Batteries	Energy deliv.,kWh	Energy deliv.,%	Effective duration,hrs	Parity,%
0	8.60	94.18	2.87	81.44
1	9.07	99.30	1.27	98.89
2	9.11	99.82	0.77	99.61
3	9.12	99.91	0.54	99.75
4	9.12	99.92	0.42	99.77

TABLE V: Distribution of dispensed energy by max charging speed. Domestic chargers.

EV Charging Speed range, kW	Energy (median),kWh	Energy (mean), kWh
0..3	6.4	6.97
3..7	7.0	8.10
7..11	9.7	12.23
11.22	8.0	9.96

a single battery. The actual utilisation may be higher as a battery may discharge and then charge within the same plugin session, however the results provide a baseline for battery life estimation.

### B. Local Authority Charger Analysis

For local authority chargers we evaluate sessions with maximum charging speeds ranging from 3 to 100 kW, which represent 98.7% of all charging sessions. Table VI compares mean delivered energy, mean effective duration and parity rate for local authority chargers. The results indicate that 3 kW grid supply even in combination with high number of batteries is not sufficient to replace high-speed grid connections. With

TABLE VI: Performance of Local Authority chargers

Batteries	Energy deliv.,kWh		Energy deliv.,%		Effec. dur,hrs		Parity,%	
	3kW	7kW	3kW	7kW	3kW	7kW	3kW	7kW
0	1.79	3.8	15.57	33.12	0.59	0.541	3.62	12.82
1	4.21	5.94	36.64	51.8	0.53	0.498	14.44	22.96
2	6.22	7.67	54.16	66.9	0.49	0.454	25.03	39.09
3	7.78	8.97	67.71	78.2	0.45	0.411	41.04	52.51
4	8.88	9.92	77.33	86.5	0.41	0.370	53.44	63.75
5	9.63	10.57	83.85	92.1	0.37	0.334	63.15	73.30
6	10.12	11.06	88.15	96.4	0.34	0.302	71.20	80.67
7	10.44	11.36	90.93	99.00	0.31	0.273	77.52	90.77
8	10.62	11.43	92.53	99.6	0.29	0.245	88.22	99.45
9	10.66	11.44	92.87	99.7	0.26	0.222	92.31	99.57
10	10.68	11.44	93.06	99.7	0.24	0.203	92.54	99.63

TABLE VII: Distribution of dispensed energy by max charging speed. Local authority chargers

EV Charging Speed, kW	Energy(median), kWh	Energy(mean), kWh
0..11	3.95	5.91
11..22	5.70	5.35
22..50	9.48	11.17
50...	8.34	9.68

a single battery, the battery-assisted charger can deliver only 36.64% of energy achieving parity for only 14.44% sessions. As the number of batteries is increased to 10, the average delivered energy reaches 93.06% with 92.54% sessions achieving parity. The average effective duration with one battery is 0.5331 hours, which is 2.09 times slower than that of raw charging; as the number of batteries is increased to 10, the average effective duration approaches 0.2383. Increasing the

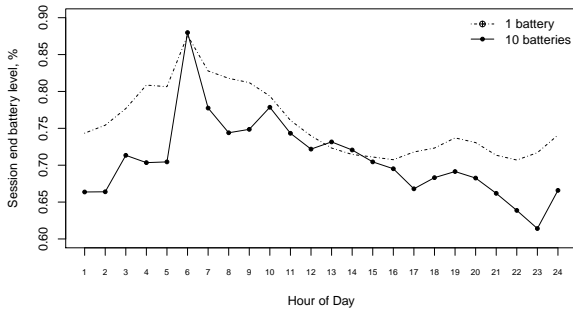


Fig. 4: Mean battery charge levels by charging session start times for 1 and 10 batteries respectively. Local authority charge points with 3 kW supply.

electric supply to 7 kW allows to achieve parity for 99.45% of sessions with 8 batteries per charge point. Similarly to domestic chargers, higher capacity charge points dispense on average more energy, Table VII.

*Battery utilisation:* Fig 4 shows average battery charge levels for 1 and 10 batteries respectively. Each point on a graph shows a mean battery charge level for all sessions that ended at that particular hour of a day. Interestingly, the mean session end battery level for a single battery pack is higher than for 10 batteries. The explanation is that for the same amount of battery level (in terms of energy), a larger battery will discharge quicker due to higher power output. The battery pack was fully drained only for 1.7%, 5.9% and 7.5% charging sessions for 1, 5 and 10 batteries respectively. The analysis shows that the battery utilisation ranges from 0.08 to 491 cycles with a mean of 62 for a single battery pack, whereas the utilisation for a 10 battery pack ranges from 0.012 to 171 cycles with a mean of 24. Increasing the battery capacity reduces the wear as expected, and the values obtained through simulation can provide a useful insight into the expected longevity and costs of battery-assisted system.

## VI. CONCLUSIONS

Electric vehicles have gained popularity recently due to their environmental benefits and energy efficiency, with governmental policies creating incentives to drive their ownership rates. As the charging rate of a vehicle increases, so does the demand for the peak power and supply capacity of electricity grid [17]. Battery-assisted charging can facilitate the adoption of electric vehicles through lowering the cost barrier to introducing high-speed charging. In this paper, we have developed a model for battery-assisted EV charge point and evaluated its performance against two publicly available charge point usage datasets in terms of delivered energy, effective charge duration and battery utilisation. Using simulations we analysed how battery-assisted charging technology can both compliment and act as replacements to high-speed chargers.

The results demonstrate that in 98.89% of domestic charging sessions, battery-assisted chargers were able to yield complete

performance parity with domestic high-speed chargers (those rated between 3 kW and 22 kW) with just a single 13.5 kWh battery using a standard 3 kW grid supply. For local authority high-speed chargers, we have shown that a combination 7 kW supply with 108 kWh battery can achieve parity in terms of delivered energy for 99.45% of all charging sessions. The renewable energy sources such as photovoltaics or wind generators can be used to further reduce the peak demand on the grid. Integrating these factors into analysis is a potential future work.

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